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㉒ Electrically controlled optical device.

㉓ An electrically controlled optical device effective index includes a traveling wave electrode (4, 5), a shield conductor (9) and a thick buffer layer (3) of a low dielectric constant. The thickness of an overlaid layer (8) disposed between the traveling wave electrode (4, 5) and the shield conductor (9) as well as the thickness of the buffer layer (3) is so determined that an effective index of a microwave transmitted through the traveling wave electrode (4, 5) approaches an effective index of light transmitted through an optical waveguide (2), and that a microwave conductor loss is reduced, and that a characteristic impedance of said traveling wave electrode (4, 5) approaches a characteristic impedance of an associated external microwave circuit.

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## ELECTRICALLY CONTROLLED OPTICAL DEVICE

The present invention relates to electrically controlled optical devices with a high operating speed, such as a light intensity modulator, a light phase modulator and an optical switch, and also to a method of producing such electrically controlled optical devices.

For the better understanding of a conventional electrically controlled optical devices, one example of a conventional Mach-Zehnder light intensity (optical) modulator is shown in Figs. 1A and 1B which are a plan view thereof and a cross-sectional view taken along the line A-A', respectively. In this example, Mach-Zehnder optical waveguides 2 are formed by Ti thermal diffusion in a Z-cut substrate 1 of LiNbO<sub>3</sub> having electro-optic effects. A buffer layer 3 of SiO<sub>2</sub> of a thickness D (Usually, D is 2000 to 3000 Å) is formed on the substrate 1, and a coplanar waveguide (CPW) composed of a center electrode 4 and earth electrodes 5 is formed on the buffer layer 3. Each termination resistor 6 is connected between the CPW electrodes 4 and 5. A feeder 7 is connected to the electrodes 4 and 5 to supply a modulating microwave signal thereto.

The electrode 4 and the electrodes 5 are generally called "CPW electrodes", and are constituted as a traveling wave electrode. With respect to the dimensions of these electrodes, the thickness of the electrodes 4 and 5 is usually 1 to 3 μm, and the width 2W of the center electrode 4 is 35 μm, and a gap 2G between the center electrode 4 and the earth electrode 5 is 6 μm. Since the characteristic impedance of the CPW electrodes is 21Ω, 43Ω is selected as the value of the termination resistor 6.

Generally, in an optical modulator, when a driving electric power is supplied from the modulating microwave signal feeder 7, an electric field is applied between the center electrode 4 and the earth electrode 5. Since the LiNbO<sub>3</sub> substrate 1 has electro-optic effects, a change in refractive index occurs due to this electric field. As a result, the lights propagated respectively through the two optical waveguides 2 are shifted in phase from each other. When this phase shift reaches the level of  $\pi$ , the lights radiate in to the substrate at a light-mixing portion of the Mach-Zehnder optical waveguide, so that an OFF condition develops. In this optical modulator, since the CPW electrodes 4 and 5 are constituted as a traveling wave electrode, such a limitation as is encountered in an electrical circuit is ideally not imposed on the bandwidth. Furthermore, in so far as the modulating microwave signal wave propagated through the CPW electrodes 4 and 5 agrees in propagating velocity with the light propagated through the optical waveguide

2, the modulation bandwidth is not limited, and therefore the optical modulator can operate at high speed.

Actually, however, there is a difference between the velocity of the microwave and the velocity of the light, and the modulation bandwidth is limited by it. A 3dB modulation bandwidth Δf resulting from this velocity mismatch is expressed by the following formula (Reference literature: Journal of Institute of Electronics and Communication Engineers of Japan, (C), J64-C, 4, p.264-271, 1981) :

$$\Delta f = 1.9 c / (\pi L |n_m - n_o|) \quad (1)$$

where n<sub>m</sub> represents a microwave effective index of the substrate 1 with respect to the signal wave, n<sub>o</sub> represents an effective index of the light, L represents the length of the portion of the CPW electrode 4, 5 interacting with the optical waveguide 2, and c represents the light velocity.

Here, the modulation bandwidth Δf represents a 3dB modulation bandwidth in optical power. In the above reference literature, the 3dB modulation bandwidth is indicated in terms of an electric level when the above optical power is converted by a light-receiving device. Therefore, the factor "1.9" in the formula (1) is obtained through conversion of a factor "1.4" of the above reference literature.

The relation of the above microwave effective index n<sub>m</sub> with an effective dielectric constant ε<sub>eff</sub> - (effective relative permittivity) of the substrate 1 is expressed in the following:

$$n_m = \sqrt{\epsilon_{eff}} \quad (2)$$

In a substrate material having electro-optic effects, the microwave effective index n<sub>m</sub> with respect to a signal wave is usually greater than the effective index n<sub>o</sub> with respect to light. The effective dielectric constant ε<sub>eff</sub> of the substrate 1 is determined mainly by the dielectric constant ε<sub>r2</sub> and thickness of the substrate material, the gap 2G between the CPW electrodes 4 and 5, an operating frequency, etc. From the viewpoint that the substrate can be easily handled when producing it, the thickness of the substrate is usually 0.5 mm to several millimeters. Since the thickness of the substrate is usually sufficiently greater than the electrode gap 2G, the following formula is established:

$$\epsilon_{eff} \approx (\epsilon_{r2} + 1)/2 \quad (3)$$

The dielectric constant of the LiNbO<sub>3</sub> substrate is nearly equal to 35 (i.e., ε<sub>r2</sub> ≈ 35), and from the formulas (2) and (3), the microwave effective index n<sub>m</sub> is nearly equal to 4.2 (i.e., n<sub>m</sub> ≈ 4.2). Since the effective index n<sub>o</sub> with respect to light is 2.1 (i.e., n<sub>o</sub> = 2.1), the microwave effective index n<sub>m</sub> is about twice greater than the effective index n<sub>o</sub>.

Therefore, when the operation is to be effected at 9 GHz, around 10 mm is selected, from the

formula (1), as the length L of the portion of the CPW electrodes 4 and 5 interacting with the optical waveguide.

In order that a conventional optical modulator shown in Figs. 1A and 1B can operate at high speed, it will be appreciated from the formula (1) that the length L of the CPW electrodes 4 and 5 need be shortened in accordance with the operating frequency. However, when the electrode length L is shortened, the driving voltage of the optical modulator becomes higher, which results in a disadvantage that the modulation efficiency is lowered.

Figs. 2A and 2B show an optical modulator disclosed by some of the present inventors and others in earlier Japanese Patent Application Laying-Open No. 48021/89. In this optical modulator, a shield conductor 9 is provided on electrodes 4 and 5 through an overlaid layer 8. The overlaid layer 8 is made of polyimide or air. By reducing a thickness H of the overlaid layer 8 (that is, bringing the shield conductor 9 closer to the electrodes 4 and 5), the microwave effective index  $n_m$  can be decreased, thereby decreasing the velocity mismatch between the microwave and the light.

However, in this optical modulator of the above earlier application, the effect of decreasing the microwave effective index  $n_m$  by a buffer layer 3 is not efficiently utilized. Therefore, if it is intended to sufficiently match the velocity of the microwave to that of the light, the characteristic impedance of the CPW electrodes 4 and 5 decreases too much, as compared with the case where the shield conductor 9 is not used. As a result, the CPW electrodes 4 and 5 can not match an external microwave circuit. Moreover, if in view of this impedance decrease due to the shield conductor 9, a gap 2G is increased (that is, the characteristic impedance is set to a high value), the intensity of the electric field acting on an optical waveguide 2 is weakened, so that the driving voltage is increased. Further, since the shield conductor 9 is disposed close to the CPW electrodes 4 and 5, the microwave conductor loss becomes large as later described.

Figs. 3A and 3B show an optical modulator disclosed by some of the present inventors and others in earlier Japanese Patent Application No. 201491/88. In this optical modulator, a width 2W of a center electrode 4 is approximately equal to that of an optical waveguide 2, and a buffer layer of  $\text{SiO}_2$  has an increased thickness D, thereby improving the characteristics.

The characteristics of this earlier example are shown in Fig. 4. Fig. 4 shows the results of analysis of the relation of the microwave effective index  $n_m$  and the characteristic impedance  $Z_o$  with the thickness D of the buffer layer 3 when the width 2W of a central conductor portion of the CPW

electrode 4 is 8  $\mu\text{m}$ , and the gap width 2G is 15  $\mu\text{m}$ . In this analysis, the evaluation is made using a spectral domain method (Kawano: "Hybrid-mode analysis of a broadside-coupled microstrip line", IEE Proc. Pt. H, vol.131, pp.21-24, 1984) which can strictly deal with a dielectric multi-layer structure.

As can be seen from Fig. 4, with an increase of the thickness of the buffer layer 3, the microwave effective index  $n_m$  decreases, and hence  $|n_m - n_0|$  decreases. As a result, the product of the 3dB modulation band and interaction length ( $\Delta f \cdot L$ ) can be increased, as shown in Fig. 5. In Fig. 5, the axis of ordinates represents the product ( $\Delta f \cdot L$ ) of the 3dB modulation band  $\Delta f$  and the length L of the CPW electrode. Hereinafter,  $\Delta f \cdot L$  or  $\Delta f$  will be often referred to as "(3dB) modulation band".

When the voltage for switching the light output from an ON condition to an OFF condition (that is, a half-wave voltage  $V_\pi$ ) is small, a higher efficiency is achieved. Fig. 6 shows the relation between the thickness D of the buffer layer 3 and the product ( $V_\pi \cdot L$ ) of the half-wave voltage  $V_\pi$  and the interacting length L.

As indicated in the formula (1), the modulation band  $\Delta f$  is in inverse proportion to the mismatch between the effective index  $n_m$  of the microwave and the effective index  $n_0$  of the light. Therefore, as shown in Fig. 5, the thickness D of the buffer layer becomes large, and as the mismatch between the effective index  $n_m$  of the microwave and the effective index  $n_0$  becomes small, the rate of increase of the modulation band becomes high.

On the other hand, as shown in Fig. 6,  $V_\pi \cdot L$  increases substantially linearly with an increase of the thickness d of the buffer layer 3. The ratio of  $\Delta f \cdot L$  to  $V_\pi \cdot L$  ( $\Delta f/V_\pi$ ) represents a modulation index, and it is desirable that this value is high. As shown in Fig. 7,  $\Delta f/V_\pi$  tends to increase with an increase of the thickness D of the buffer layer 3, but a marked improvement in optical modulation efficiency can not be expected.

Also, as shown in Fig. 4, when the thickness of the buffer layer 3 is increased, the value of the characteristic impedance  $Z_o$  tends to increase, so that it is difficult to achieve a matching with an external circuit. Therefore, in view of the impedance matching with the external circuit, if  $Z_o$  is determined to be about  $50 \pm 10 \Omega$ , then it is necessary that the thickness D of the buffer layer 3 be set to not more than about 1  $\mu\text{m}$ .

Accordingly, as is clear from Fig. 7,  $\Delta f/V_\pi$  is not more than 1.7. Also, when the length L is increased, the microwave conductor loss and the value of a dc resistance are increased, which makes it difficult to obtain good modulation characteristics.

Fig. 8 shows an optical modulator invented by Mitomi et al. and disclosed in Japanese Patent

Application Laying-Open No. 91111/89. Fig. 9 shows an optical modulator proposed in Second Optoelectronics Conference (OEC '88) Post-Deadline Papers Technical Digest, PD-1 (October 1988, Tokyo).

In Fig. 8, the thickness of traveling wave electrodes 10 and 11 (here, asymmetrical coplanar strip is used as one example) is increased in an attempt to decrease a microwave effective index  $n_m$ . With this construction, the characteristic impedance  $Z_o$  is also decreased together with the microwave effective index  $n_m$ .

Fig. 9 shows a structure which improves such characteristics. In this case, the thickness D of a buffer layer 3 is increased to about 1  $\mu\text{m}$  so as to increase the characteristic impedance  $Z_o$ , thereby compensating for the reduction of  $Z_o$  caused when the thickness of electrodes 10 and 11 is increased to 10  $\mu\text{m}$ . Further, as described above for the prior art of Fig. 3 with reference to the formula (1) and Fig. 7, the increase of the thickness of the buffer layer 3 also improves the value of  $\Delta f/V\pi$ . However, in order to achieve a velocity matching between the light and the microwave, it is necessary to set the thickness of the electrodes to not less than 10  $\mu\text{m}$ , and there are inevitably encountered manufacturing difficulties such as a short circuit between the electrodes 11. Therefore, with this technique, it is difficult to carry out a light modulation of a very wide band.

As described above, with the conventional constructions, the matching of the characteristic impedance can not be sufficiently achieved, or the microwave conductor loss can not be kept to a low level, or the half-wave voltage can not be decreased, or the velocity of the microwave can not match the velocity of the light wave. Therefore, it has been very difficult to achieve both of a wide band characteristic and a low driving voltage characteristic.

It is therefore a first object of the present invention to provide an electrically controlled optical devices which is rendered highly efficient at a wide band by overcoming the above-mentioned problems, such as a characteristic impedance mismatching between an electrode and an external circuit, an increase of a microwave conductor loss, an increase of a half-wave voltage, and a mismatching between the velocity of light and the velocity of the microwave.

When such an electrically controlled optical device having a high efficiency at a wide band is actually to be produced, there are used known techniques such as air bridge commonly used in the manufacture of a microwave integrated circuit. However, in this case, it is necessary to precisely form an overlaid layer of not more than 10  $\mu\text{m}$  thickness over a length of several centimeters, and

therefore the fabrication cannot be effected easily, thus making its manufacture difficult.

Therefore, a second object of the present invention is to provide a method of easily producing such an electrically controlled optical device highly efficient at a wide band, which method overcomes the above difficulties heretofore involved in the manufacture of the electrically controlled optical device.

- 10 In order to achieve the above first object, according to the present invention, there is provided an electrically controlled optical device comprising: a substrate having electro-optic effects and having at least one optical waveguide;
- 15 a buffer layer provided on the substrate; a traveling wave electrode provided on the buffer layer and comprising a center electrode and earth electrodes; and
- 20 a shield conductor provided near to a region where the optical waveguide interacts with the traveling wave electrode, the shield conductor confronting the traveling wave electrode through an overlaid layer;
- 25 the thickness of the buffer layer and the thickness of the overlaid layer being so determined that a microwave effective index of the substrate with respect to a modulating microwave signal applied to the traveling wave electrode approaches an effective index of light propagated through the optical waveguide, and also that a characteristic impedance of the traveling wave electrode approaches a characteristic impedance of an associated external microwave circuit.
- 30

The thickness of the overlaid layer is 3 to 10  $\mu\text{m}$  if its dielectric constant is about 1 (for example, air). The thickness of the buffer layer is 0.5 to 2.0  $\mu\text{m}$  if its dielectric constant is not more than 4.5 (for example, silicon dioxide or Teflon).

In the above construction, the thickness of the buffer layer is much increased as compared with the prior art, and the shield conductor is provided. Therefore, a broad-band light modulation can be achieved without unduly increasing the driving voltage.

The inventors of the present invention have attempted to further enhance a performance of the above electrically controlled optical device of the present invention, and have found that this electrically controlled optical device can be further improved in the following points:

In the above electrically controlled optical device of the present invention, it is necessary to use the thick buffer layer in order to reduce the microwave propagation loss and to reduce a velocity mismatching between the microwave and the light. Therefore, the interaction between the microwave and the light wave is less active. Further, in this electrically controlled optical device, since the

earth electrodes are wide, the lines of electric forces from the center electrode are distributed widely over the earth electrode, and as a result the efficiency of overlapping (i.e., interaction) between the microwave and the light is about five times greater at the central electrode than at the earth electrode. Therefore, in order to keep the driving voltage to not more than 5 V at an operating wavelength of 1.5  $\mu\text{m}$ , it is necessary that the length L of interaction between the microwave and the light should be long on the order of about 2.7 cm. Therefore, because of a microwave conductor loss, the 3dB modulation band is limited to 20 GHz at best.

In the present invention, in order to lessen such band limitation due to the increased microwave conductor loss, the buffer layer is made of a material (for example, a Teflon-type resin; dielectric constant  $\epsilon = 1.9$ ) which is lower in dielectric constant than the heretofore-used materials such as silicon dioxide,  $\text{SiO}_2$  ( $\epsilon = 3.9$ ) and alumina,  $\text{Al}_2\text{O}_3$  ( $\epsilon = 9.6$ ).

With this construction, the buffer layer can be greatly reduced in thickness as compared with the conventional silicon dioxide layer. Therefore, when the driving voltage is designed to be the same as that of the prior art, the electrode length can be reduced, which enables the modulation band to be widened greatly. Also, when the electrode length is designed to be the same as that of the prior art, the driving voltage can be reduced greatly.

Further, in the present invention, in order to overcome the band limitation due to the increased microwave conductor loss, at least those portions of the substrate disposed close to the electrodes are recessed, and at a region where light and a microwave interact with each other, part or the whole of the traveling wave electrode is disposed out of contact with that portion of the substrate disposed close to the optical waveguide, so that the microwave conductor loss is reduced, and that an effective index of the microwave conductor through the traveling wave electrode approaches an effective index of the light propagated through the optical waveguide, and that an characteristic impedance of the traveling wave electrode approaches a characteristic impedance of an associated external circuit.

With this construction, the lines of electric force interconnecting the center electrode and the earth electrode perceive the thick buffer layer of a low dielectric constant (for example, the dielectric constant of  $\text{SiO}_2$  is about 4), and therefore the microwave effective index can be reduced as in the case where the buffer layer is uniformly thick. On the other hand, the depth from the interface between the air and the buffer layer to the optical waveguide can be reduced as compared with the case where

the buffer layer is uniformly thick. Therefore, the efficiency of interaction between the microwave and the light becomes higher, so that the driving voltage can be reduced. As a result, the interacting length can be reduced, so that the band can be widened.

Fig. 10 shows a velocity matching-type optical modulator proposed by Sato et al. in Journal of Institute of Electronics and Communication Engineers of Japan (vol. J.69-C, pp.129- 1296, 1986). At a glance, this construction is similar to the above construction of the present invention, but differs therefrom in that edges of electrodes 10 and 11 which produce an electric field of high intensity are disposed in contact with a substrate 1 of a high dielectric constant (The value of this dielectric constant is approximately 35, taking the anisotropy into consideration), and that a shield conductor is not provided. Because of these differences, the microwave effective index is not reduced sufficiently, and as a result, this conventional optical modulator suffers from the drawback that it is difficult to achieve a complete velocity matching.

Fig. 11 shows a construction proposed by Izutzu et al. in literature named "Picosecond Electronics and Optoelectronics (G. A. Mourou et al. ed.), pp. 172-175, Springer-Verlag, 1985. At a glance, this construction is also similar to the above construction of the present invention, but differs therefrom in that a substrate is not recessed at those portions thereof disposed close to electrodes, and that a shield conductor is not provided. Therefore, a microwave effective index can not be greatly reduced, which results in a drawback that it is difficult to achieve a complete velocity matching.

Further, in the present invention, in order to overcome the above band limitation due to the increased microwave conductor loss, a slot is formed through at least one of the earth electrodes.

With this construction, it is possible to interact the microwave and the light at a high efficiency to decrease the driving voltage. As a result, the interacting length can be reduced, and a broad-band light modulation can be achieved.

In order to achieve the above second object (that is, to provide a method of easily producing an electrically controlled optical device effective index highly efficient at a wide band), according to the present invention, the following procedure is adopted.

There is used a substrate having electro-optic effects and having at least one optical waveguide. A traveling wave electrode is formed, above a buffer layer, on the substrate in the vicinity of the optical waveguide to form at least one optical control portion, thereby providing an electrically controlled optical device. Further, a preformed conductor which can precisely determine the thickness of

an overlaid layer is fixed in the vicinity of the electrode of the electrically controlled optical device.

With this method, the overlaid layer of not more than 10  $\mu\text{m}$  thickness can be formed over a length of several centimeters without the need for advanced fabricating techniques, and therefore the high-speed and broad-band electrically controlled optical device of the velocity matching-type can be easily produced.

The above and other objects, effects, features and advantages of the present invention will become more apparent from the following description of embodiments thereof taken in conjunction with the accompanying drawings.

Fig. 1A is a plan view of a conventional Mach-Zehnder light intensity (optical) modulator;

Fig. 1B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 1A;

Fig. 2A is a plan view of an optical modulator disclosed in an earlier Japanese patent application;

Fig. 2B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 2A;

Fig. 3A is a plan view of an optical modulator disclosed in an earlier Japanese patent application;

Fig. 3B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 3A;

Fig. 4 is an illustration showing the relation of a thickness D of a buffer layer with a microwave effective index  $n_m$  and a characteristic impedance  $Z_0$  in the optical modulator of Figs. 3A and 3B;

Fig. 5 is an illustration showing the relation between a 3dB light modulation band  $\Delta f^*L$  and the thickness D of the buffer layer in the optical modulation of Figs. 3A and 3B;

Fig. 6 is an illustration showing the relation between the product  $(V\pi^*L)$  of a half-wave voltage  $V\pi$  and an interacting length L and the thickness D of the buffer layer in the optical modulator of Figs. 3A and 3B;

Fig. 7 is an illustration showing the relation between the ratio  $(\Delta f/V\pi)$  and the thickness D of the buffer layer in the optical modulator of Figs. 3A and 3B;

Fig. 8 is a fragmentary cross-sectional view of an optical modulator disclosed in an earlier Japanese patent application;

Fig. 9 is a fragmentary cross-sectional view of a further conventional optical modulator;

Figs. 10 and 11 are cross-sectional views of further conventional optical modulators, respectively;

Fig. 12A is a plan view of a first embodiment of the present invention;

Fig. 12B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 12A;

Fig. 13 is an illustration showing the relation of a thickness H of an overlaid layer with a micro-

wave effective index  $n_m$  and a characteristic impedance  $Z_0$  in the first embodiment;

Fig. 14 is an illustration showing the relation between a light modulation band  $\Delta f^*L$  and the thickness H of the overlaid layer in the first embodiment, in which a microwave conductor loss  $\alpha$  is not taken into consideration;

Fig. 15 is an illustration showing the relation between the microwave conductor loss through a traveling wave electrode and the thickness H of the overlaid layer in the first embodiment;

Fig. 16 is an illustration showing the relation between  $V\pi^*L$  and the thickness of the overlaid layer in the first embodiment;

Fig. 17 is an illustration showing the relation between the ratio  $(\Delta f/V\pi)$  and the thickness H of the overlaid layer in the first embodiment;

Fig. 18A is a fragmentary cross-sectional view of a modified form of the present invention, using an asymmetrical coplanar strip as electrodes;

Fig. 18B is a fragmentary cross-sectional view of another modified form of the invention, using a directional coupler as optical waveguides, thereby providing an optical modulator or an optical switch;

Fig. 19A is a plan view of an electrically controlled optical device according to a second embodiment of the present invention;

Fig. 19B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 19A;

Figs. 20A and 20B are illustrations showing the profile of a microwave electric field in the direction of the depth;

Fig. 21 is an illustration showing the relation between the product  $(V\pi^*L)$  of a half-wave voltage (driving voltage) and an electrode length and a thickness of a buffer layer in the present invention;

Fig. 22 is an illustration showing calculation results of modulation bands in an electrically controlled optical device to which the present invention is applied;

Fig. 23A is a plan view of a third embodiment of the present invention;

Fig. 23B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 23A;

Fig. 24 is an illustration showing the relation of a depth of recessing with a microwave effective index and a characteristic impedance;

Fig. 25 is an illustration showing the relation between the depth of recessing and a microwave conductor loss  $\alpha$ ;

Fig. 26 is an illustration showing the relation between a thickness of that portion of a buffer layer just above an optical waveguide and the product  $(V\pi^*L)$  of a half-wave voltage  $V\pi$  and an interacting length L;

Fig. 27A is a plan view of a fourth embodiment of the present invention;

Fig. 27B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 27A;

Fig. 28A is a plan view of a fifth embodiment of the present invention;

Fig. 28B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 28A;

Fig. 29A is a plan view of a sixth embodiment of the present invention;

Fig. 29B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 29A;

Fig. 30A is a plan view of a seventh embodiment of the present invention;

Fig. 30B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 30A;

Fig. 31 is an illustration explanatory of the operation of the seventh embodiment;

Fig. 32A is a plan view of an eighth embodiment of the present invention;

Fig. 32B is a fragmentary cross-sectional view taken along the line A-A' of Fig. 32A;

Figs. 33A to 33C are views showing the steps of producing an electrically controlled optical device according to a ninth embodiment of the present invention;

Figs. 34A to 34C are cross-sectional views of shield conductors, respectively;

Fig. 35 is an illustration showing light-frequency response characteristics of the electrically controlled optical device of the ninth embodiment; and

Figs. 36A to 36D are views showing the steps of producing an electrically controlled optical device effective index according to a tenth embodiment of the present invention.

Preferred embodiments of the invention will now be described in detail with reference to the drawings.

### First Embodiment

Fig. 12A is a plan view of a first embodiment of the invention, and Fig. 12B is a fragmentary, enlarged cross-sectional view taken along the line A-A' of Fig. 12A: In Fig. 12A, a shield conductor 9 is omitted for illustration purposes.

In this embodiment as in the conventional example of Figs. 3A and 3B, a center electrode 4 and earth electrodes 5, which serve as a traveling wave electrode, are disposed above a substrate 1 of LiNbO<sub>3</sub> having electro-optic effects and having two optical waveguides 2. In this embodiment, the shield conductor 9 is arranged through an overlaid layer 8 in the vicinity of a region where the optical waveguides 2 interact with the traveling wave electrodes 4 and 5. In this optical modulator of the above construction, the thickness of a buffer layer 3 and the thickness of the overlaid layer 8 are so

determined that a microwave effective index  $n_m$  of the substrate 1 with respect to a modulating microwave signal supplied from a feeder 7 to the traveling wave electrodes 4 and 5 approaches an effective index  $n_o$  of light propagated through the optical waveguides 2, and that a characteristic impedance  $Z_o$  of the traveling electrodes 4 and 5 approaches a characteristic impedance of an associated external microwave circuit.

5 In this embodiment, a width 2W of the center electrode 4 is 8  $\mu\text{m}$ , and a gap 2G between the electrode 4 and the electrode 5 is 15  $\mu\text{m}$ , and a width of the optical waveguide 2 is 6  $\mu\text{m}$  and hence is generally equal to the width of the center electrode 4. A thickness D of the buffer layer 3 of SiO<sub>2</sub> is 1.2  $\mu\text{m}$ .

10 In this embodiment, the relation of the microwave effective index  $n_m$  and the characteristic impedance  $Z_o$  with the thickness H of the overlaid layer 8 is analyzed according to the analysis procedure used in Fig. 4, and the results of this analysis are shown in Fig. 13.

15 In the optical modulator of this embodiment using the Z-cut LiNbO<sub>3</sub> substrate 1, it is absolutely necessary to provide the buffer layer 3 in order to reduce a loss resulting from the absorption of the light (which is propagates through the waveguides 2) by the electrodes 4 and 5. Here, however, in order to clarify the influence of the buffer layer 3, the calculation results both in the case of D = 1.2  $\mu\text{m}$  and in the case of D = 0  $\mu\text{m}$  are shown in Fig. 13.

20 As can be seen from Fig. 13, as the thickness H of the overlaid layer 8 increases,  $n_m$  and  $Z_o$  approach to respective constant values. In the case where the shield conductor 9 is not provided (that is, in the case of the prior art of Figs. 3A and 3B), such constant values correspond to the calculated values shown in Fig. 4. In Fig. 13, the constant values in the case of D = 1.2  $\mu\text{m}$  are indicated by a circle mark, and the constant values in the case of D = 0  $\mu\text{m}$  are indicated by triangular marks, and the values corresponding to these values are indicated by identical marks in Fig. 4.

25 As can be seen from these Figures, irrespective of the thickness D of the buffer layer 3, as the thickness H of the overlaid layer 8 decreases, the value of the microwave effective index  $n_m$  decreases and approaches the effective index  $n_o$  of the optical waveguide 2, and also the characteristic impedance  $Z_o$  decreases. However, in the case of D (thickness of the buffer layer 3) = 0, when the thickness H of the overlaid layer 8 is so selected that  $n_m$  becomes equal to  $n_o$  (= 2.1),  $Z_o$  is much lower than  $50 \pm 10 \Omega$  and is about  $16 \Omega$ . Therefore, an impedance mismatching occurs, and as a result a broad-band operation can not be expected.

30 On the other hand, in the case of D = 1.2  $\mu\text{m}$ ,

when the thickness of the overlaid layer 8 is about 5  $\mu\text{m}$ ,  $Z_0$  is about 42  $\Omega$ , and a good matching with the external circuit can be achieved, and also  $n_m$  and  $n_o$  can be close to each other. Therefore, a broad-band operation can be achieved as shown in Fig. 14. By suitably determining the thickness D of the buffer layer 3 and the thickness H of the overlaid layer 8, the desired characteristic impedance  $Z_0$  and the desired band  $\Delta f \cdot L$  can be achieved.

Fig. 15 shows the results of the calculation of a microwave conductor loss  $\alpha$  according to the thickness H of the overlaid layer 8 in the embodiment of Figs. 12A and 12B. Here, the thickness D of the buffer layer 3 is used as a parameter. As can be seen from Fig. 15, when the thickness D of the buffer layer 3 is large, the microwave conductor loss  $\alpha$  can be reduced, which is advantageous for a broad-band operation.  $\alpha$  increases with a decrease of H, but it is clear from Fig. 15 that the degree of such increase is small.

Fig. 16 shows the results of the calculation of  $V_{\pi} \cdot L$  according to the thickness H of the overlaid layer 8 in the embodiment of Figs. 12A and 12B. Here, the thickness D of the buffer layer 3 is 1.2  $\mu\text{m}$ . As can be seen from Fig. 16, the influence of the thickness H of the overlaid layer 8 on  $V_{\pi} \cdot L$  is sufficiently small.

Fig. 17 shows the value of  $\Delta f/V_{\pi}$  when the thickness H of the overlaid layer 8 is used as a variable. This value is small, that is, less than 2, in the prior art shown in Fig. 7. However, as can be seen from Fig. 17, in this embodiment,  $\Delta f/V_{\pi}$  can be increased greatly.

As described above, in this embodiment, when the thickness D of the buffer layer 3 of  $\text{SiO}_2$  is 1.2  $\mu\text{m}$ , a light modulation can be achieved at an extremely broad band if the thickness H of the overlaid layer 8 is in the range of between about 5  $\mu\text{m}$  and about 10  $\mu\text{m}$ . Therefore, when the length L of the CPW electrodes 4 and 5 (that is, the length L of interaction between the microwave and the light) is 2 cm, the half-wave voltage can be set to a low level of about 6.7 V at a light modulation band of several tens to several hundreds GHz. Also, the characteristic impedance  $Z_0$  can be set to 44 to 55  $\Omega$ , and can well match the characteristic impedance of the external circuit.

In this embodiment, although the thickness D of the  $\text{SiO}_2$  buffer layer 3 is 1.2  $\mu\text{m}$ , the values of D, H and 2G can be suitably changed according to the desired modulation band so that  $Z_0$  can be 50  $\Omega$ .

Although the substrate 1 having the optical waveguides 2 formed therein is made of  $\text{LiNbO}_3$ , the substrate can be made of any other suitable material having electro-optic effects, such as  $\text{LiTaO}_3$  and  $\text{KTiOPO}_4$ .

Further, by using linear optical waveguides or a directional coupler as the optical waveguides 2, a phase modulator or a switch can be constructed. Further, the optical waveguides 2 can be formed by an ion exchange or the formation of ridges, instead of the Ti thermal diffusion.

In this embodiment, although the traveling wave electrodes 4 and 5 have been described as the CPW electrodes, the traveling wave electrodes can be constituted, for example, as asymmetrical coplanar strip electrodes 10 and 11 as shown in Figs. 18A and 18B. The electrodes 10 and 11 are respectively a central electrode and an earth electrode of the asymmetrical coplanar strip formed on the buffer layer 3 of  $\text{SiO}_2$ .

In the structure of Fig. 18A, Mach-Zehnder optical waveguides are used as the optical waveguides 2. Fig. 18B shows an optical switch employing a directional coupler in which two optical waveguides 2 are connected together and disposed close to each other.

If linear waveguides are used, an optical phase modulator can be constructed, in which case an X-cut substrate may be used as a  $\text{LiNbO}_3$  substrate.

## Second Embodiment

Figs. 19A and 19B show a second embodiment of an electrically controlled optical device of the present invention. This embodiment of Fig. 19 differs from the prior art of Figs. 1 and 2 in that a buffer layer 3 is made of a Teflon (polytetrafluoroethylene)- type resin (dielectric constant :  $\epsilon = 1.9$ ) instead of silicon dioxide ( $\text{SiO}_2$ ; dielectric constant:  $\epsilon \approx 3.9$ ). Such Teflon- type resins are, for example, those (dielectric constant:  $\epsilon \approx 1.9$ ; refractive index:  $n \approx 1.3$ ) described in Nikkei New Material, 8-7, p.17, 1989, and the buffer layer 3 can be provided by forming such a Teflon-type material into a thickness of not more than 1  $\mu\text{m}$ , using spin coating, sputtering or the like.

Fig. 20 shows a profile of the intensity of the electric field in the direction of the depth in the embodiment of Fig. 19, in the case where traveling wave electrodes formed on the buffer layer 3 comprises a center electrode 4 having width 2W of 8  $\mu\text{m}$  and earth electrodes 5, a gap 2B between the center electrode 4 and the earth electrode 5 is 15  $\mu\text{m}$ . Fig. 20A shows the profile when the thickness of the buffer layer 3 is 0.5  $\mu\text{m}$ , and Fig. 20B shows the profile when the thickness of the buffer layer 3 is 1.2  $\mu\text{m}$ . It is clear that the thickness of the buffer layer 3 influences the interaction between the microwave and the light wave. Fig. 21 shows the calculation results representing the relation of the product ( $V_{\pi} \cdot L$ ) of the half-wave voltage (driving

voltage) and the electrode length with the thickness of the buffer layer. In the present invention, when estimating, from the difference in dielectric constant, the thickness of the buffer layer required to obtain the same  $n_m$  as in the prior art, it is found that it is possible to reduce the thickness by about 30% as compared with the prior art. Therefore, it is surmised that  $V\pi \cdot L$  can be about 3/4, which means that when the electrode length is the same, the driving voltage can be reduced by about 25%.

Fig. 22 shows the results of the calculation of the modulation band, obtained when the present invention is applied to the prior art of Fig. 2. When the prior art is so designed that the driving voltage is not more than 5 V at an operating wavelength of 1.5  $\mu\text{m}$ , the required electrode length is about 2.7 cm, and the modulation band is 20 to 30 GHz. By applying the present invention, the electrode length can be shortened to about 2.0 cm, and therefore it is surmised that the modulation band is not less than 50 GHz.

### Third Embodiment

Fig. 23 shows a third embodiment of the present invention in which an X-cut LiNbO<sub>3</sub> substrate 1 is used. In this embodiment, a thick buffer layer 3 having a low dielectric constant is disposed beneath electrodes 4 and 5, and the edges of the electrodes generating lines of strong electric forces are not disposed in contact with the substrate 1. Therefore, the effect of reducing the dielectric constant is excellent. For producing this structure, optical waveguides 2 are formed in the substrate 1 by an ordinary Ti thermal diffusion method. Then, leaving those sections of the surface portion of the substrate 1 including the optical waveguides 2, part or the whole of the remainder of the surface portion is removed by etching, so that the surface of the substrate is recessed except for the convex portions including the optical waveguides therein. Fig. 24 shows the relation of the depth of the recessing of the substrate 1 with the microwave effective index and the characteristic impedance. It can be seen from Fig. 24 that as the depth of the recessing increases, the microwave effective index decreases. Fig. 25 shows the relation between the depth of the recessing and a microwave conductor loss  $\alpha$ . It can be seen from Fig. 25 that as the depth of the recessing increases, the microwave conductor loss decreases. Fig. 26 shows the relation between the thickness of those portions of the buffer layer 3 disposed just above the optical waveguides 2 and  $V\pi \cdot L$  ( $V\pi$ : half-wave voltage;  $L$ : interacting length). In the present invention, since the thickness of those portions of the buffer layer 3 above the optical waveguides 2 is small, the driving

voltage can be kept to a low level.

In other words, in this embodiment, there are obtained not only the effect of reducing the effective index of the microwave and the microwave conductor loss which is achieved by the use of a thick buffer layer, but also the effect of restraining the increase of the driving voltage which is achieved by the use of a thin buffer layer.

### Fourth Embodiment

Fig. 27 shows a fourth embodiment of the present invention which differs from the third embodiment of Fig. 23 in that a shield conductor 9 is additionally provided, so that even if the depth of the recessing is small, a complete matching between the effective refractive indexes of the microwave and the light can be achieved. In this embodiment, since the driving voltage is as low as that in the third embodiment, the interacting length  $L$  required to obtain the desired driving voltage can be short. Therefore, the band of the light modulation can be correspondingly widened.

### Fifth Embodiment

Fig. 28 shows a fifth embodiment of the present invention in which a Z-cut LiNbO<sub>3</sub> substrate 1 is used. The principle of the widening of the band will be described with respect to a center electrode 4. In the vicinity of the electrodes, that is, at a shallow region where a buffer layer 3 exists, the electric field intensity  $E_y$  in the direction of the depth is not constant in the width  $2W$  of the center electrode 4, and becomes abruptly strong near to the edges of the electrodes. Therefore, if there exists a thick buffer layer at the region where the electric field intensity  $E_y$  in the direction of the depth is strong, this will provide an effect of reducing the microwave effective index. Practically, if the width  $2W$  of the center electrode 4 is made generally equal to or slightly greater than the width of the convex portion of the substrate including the optical waveguide therein so that the abrupt electric field in the vicinity of the edge of the electrode can perceive the thicker portion of the buffer layer, there is obtained an effect of reducing the microwave effective index.

### Sixth Embodiment

Fig. 29 shows a sixth embodiment of the present invention which differs from the fifth embodiment of Fig. 28 in that a shield conductor 9 is additionally provided, so that even if the depth of

the recessing is small, a complete matching between the effective refractive indexes of the microwave and the light can be achieved. In this embodiment, since the driving voltage is as low as that in the fifth embodiment, the interacting length L required to obtain the desired driving voltage can be short. Therefore, the band of the light modulation can be correspondingly widened.

In the above embodiments, although Mach-Zehnder optical waveguides are used as the optical waveguides, a phase modulator can be provided if only the optical waveguide disposed beneath the center electrode is used in the third and fourth embodiments, or if only one of the optical waveguides is used in the fifth and sixth embodiments.

In the above embodiments, although the electrodes are constituted by the coplanar waveguide, any other suitable electrode such as an asymmetrical coplanar strip may be used. Also, the substrate may be a Y-cut substrate of  $\text{LiNbO}_3$  and any other suitable substrate in so far as they have electro-optic effects. Further, since the shield conductor is only required to serve as an electric wall, the shield conductor is not necessarily grounded to the earth electrode, and may be supported through a spacer.

#### Seventh Embodiment

Fig. 30 shows the present invention embodied in a Mach-Zehnder light intensity modulator using a Z-cut substrate 1 of  $\text{LiNbO}_3$ . In this seventh embodiment, a slot 12 is formed through an earth electrode 5.

The width of a narrow conductor portion of the earth electrode is designated by  $2W'$ . A center electrode 4 has a width  $2W$  of 8  $\mu\text{m}$ , and a gap  $2G$  between the center electrode 4 and the earth electrode 5 is 15  $\mu\text{m}$ , and a buffer layer 3 of  $\text{SiO}_2$  has a thickness of 1.2  $\mu\text{m}$ . Fig. 31 shows the value of the product  $(V\pi \cdot L)$  of a half-wave voltage  $V\pi$  and an interacting length L when  $2W'$  is 8  $\mu\text{m}$  and a width  $2S$  of the slot 12 is a variable. As can be seen from Fig. 31, as the width  $2W'$  of the slot 12 increases, the value of the product  $(V\pi \cdot L)$  decreases. The reason for this is that the lines of electric force generated from the center electrode 4 concentrates of the narrow conductor portion (having the width  $2W'$ ) of the earth electrode 5. Therefore, the driving voltage can be reduced, and the interacting length required for obtaining the desired driving voltage can be shortened. As a result, the band can be greatly widened.

#### Eighth Embodiment

Fig. 32 shows an eighth embodiment of the present invention which differs from the seventh embodiment of Fig. 30 in that a shield conductor 9 is additionally provided, so that the effective refractive indexes of the microwave and the light can coincide with each other, thereby achieving a light modulation of a quite wide band.

In the seventh and eighth embodiments, although the Z-cut substrate 1 is used, an X-cut substrate can be used, in which case another identical slot is also formed through the other earth electrode, and the two optical waveguides are respectively disposed near to the centerlines of the gaps disposed respectively on the opposite sides of the center electrode.

#### Ninth Embodiment

Fig. 33 shows the steps of producing an electrically controlled optical device effective index according to the present invention. In Fig. 33A, optical waveguides 2 are formed in a surface of a Z-cut substrate of  $\text{LiNbO}_3$ , for example, by a Ti diffusion method. More specifically, patterns of Ti, for example, having a width of about 4 to about 9  $\mu\text{m}$  and a length of 1 to 6 cm is formed, for example, by electron beam deposition and photolithography. Thereafter, the Ti is diffused into the substrate of  $\text{LiNbO}_3$  by heat treatment to form the optical waveguides 2. Then, in Fig. 33B, using plasma CVD or the like, a  $\text{SiO}_2$  layer is formed as a buffer layer 3 on the surface of the  $\text{LiNbO}_3$  substrate 1 having the optical waveguides 2 therein. Then, by means of a vacuum deposition method or the like, a plating method and photolithography, a center electrode 4 and earth electrodes 5 are formed on the buffer layer 3, using, for example, gold (Au), the thickness of these electrodes being, for example, 4 to 5  $\mu\text{m}$ . Then, in Fig. 33C, a preformed shield conductor 9 with a groove having a depth of 0 to about 2  $\mu\text{m}$  is fixed by an adhesive, thereby completing the electrically controlled optical device effective index.

Fig. 34 shows examples of the shield conductor 9 having a groove for forming an overlaid layer 8. In Fig. 34A, the groove is formed either by a wet etching technique in which photolithography and an etchant are applied to metal or by a dry etching technique in which a plasma method or an ion beam method is used. Fig. 34B shows a structure which is designed to overcome various stability and reliability problems caused by thermal stresses due to a difference in thermal expansion coefficient between the substrate 1 and the shield conductor 9 and other factors. More specifically, using, for example, a vacuum deposition method and a plating method, a metal layer of about 10  $\mu\text{m}$  thickness for

constituting the conductor shield 9 is formed on a support base 14 which is the same material as the substrate 1 and has the same crystalline orientation as the substrate 1. Then, the groove is formed in the metal layer according to the same procedure as in Fig. 34A. In Fig. 34C, before a shield conductor 9 is formed, a groove is formed in a surface of a support base 14 either by a wet etching technique in which photolithography and an etchant are used or by a dry etching technique in which a plasma method or an ion beam method is used.

Fig. 35 shows light-frequency response characteristics of a light intensity modulator produced according to the same procedure described in Figs. 33 and 34B. More specifically, this light intensity modulator was prepared according to the following procedure. Optical waveguides 2 were formed in a substrate 1 of  $\text{LiNbO}_3$  by Ti diffusion method. Then, a buffer layer 3 of  $\text{SiO}_2$  having a thickness of  $1.2 \mu\text{m}$  was formed on the substrate 1, and then a traveling wave electrode of about  $4.5 \mu\text{m}$  thickness having a center electrode 4 and earth electrodes 5 was formed on the buffer layer 3, the width  $2W$  of the center electrode 4 being  $8 \mu\text{m}$ , and the gap  $2G$  being  $15 \mu\text{m}$ . Then, a conductor layer of gold was formed on a support base 14 of  $\text{LiNbO}_3$  by an electron beam deposition method and a plating method. Then, a groove was precisely formed in the conductor layer by photolithography and an ion beam method to form a shield conductor 9. Then, the shield conductor 9 was fixed by an adhesive so as to cover the center electrode 4 and the earth electrodes 5. In Fig. 35, marks indicate the light-frequency response characteristics before the shield conductor was attached, and a 3dB band was about 8 GHz. O marks indicate indicates the light-frequency response characteristics of the light modulator in which the depth of the groove in the shield conductor was  $0.5 \mu\text{m}$ , and the 3dB band was about 18 GHz. Δ marks indicates the light-frequency response characteristics of the light modulator in which the depth of the groove in the shield conductor was  $0.9 \mu\text{m}$ , and the 3dB band was about 15 GHz. Thus, the effects of widening the band are clear.

#### Tenth Embodiment

Fig. 36 shows a further modified embodiment. In Figs. 36A and 36B, according to the same procedure as in the ninth embodiment, optical waveguides 2, a buffer layer 3 and traveling wave electrodes 4 and 5 were sequentially formed on a substrate 1 of  $\text{LiNbO}_3$ . Then, as shown in Fig. 36C, spacers 16 of a predetermined height for controlling the thickness of an overlaid layer 8 were

formed on the electrodes 5 by photolithography and a plating method. Then, in Fig. 36D, a shield conductor 9, for example, similar to that shown in Figs. 34A and 34B but having no groove, was fixed, thereby completing an electrically controlled optical device effective index.

The invention has been described in detail with respect to preferred embodiments, and it will now be apparent from the foregoing to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects, and it is the invention, therefore, in the appended claims to cover all such changes and modifications as fall within the true spirit of the invention.

An electrically controlled optical device effective index includes a traveling wave electrode, a shield conductor and a thick buffer layer of a low dielectric constant. The thickness of an overlaid layer disposed between the traveling wave electrode and the shield conductor as well as the thickness of the buffer layer is so determined that an effective index of a microwave transmitted through the traveling wave electrode approaches an effective index of light transmitted through an optical waveguide, and that a microwave conductor loss is reduced, and that a characteristic impedance of said traveling wave electrode approaches a characteristic impedance of an associated external microwave circuit.

#### Claims

35. An electrically controlled optical device effective index comprising:  
a substrate having electro-optic effects and having at least one optical waveguide;  
a buffer layer provided on said substrate;  
40 a traveling wave electrode provided on said buffer layer and comprising a center electrode and earth electrodes; and  
a shield conductor provided near to a region where said optical waveguide interacts with said traveling wave electrode, said shield conductor confronting said traveling wave electrode through an overlaid layer;  
the thickness of said buffer layer and the thickness of said overlaid layer being so determined that a microwave effective index of said substrate with a respect to a modulating microwave signal applied to said traveling wave electrode approaches an effective index of light transmitted through said optical waveguide, and also that a characteristic impedance of said traveling wave electrode approaches a characteristic impedance of an associated external microwave circuit.
- 50 55 2. An electrically controlled optical device ef-

fective index according to claim 1, wherein said buffer layer is composed of a film of a polytetrafluoroethylene-type resin having a low dielectric constant.

3. An electrically controlled optical device effective index according to claim 1, wherein a slot is formed through at least one of said earth electrodes.

4. An electrically controlled optical device effective index comprising:  
a substrate having at least one optical waveguide;  
a buffer layer formed on said substrate; and  
a traveling wave electrode comprising a center electrode and earth electrodes;  
at least those portions of said substrate disposed close to said electrodes being recessed, and said traveling wave electrode being disposed out of contact with said substrate at a region where light and a microwave interact with each other, so that a microwave conductor loss is reduced, and that an effective index of the microwave transmitted through said traveling wave electrode approaches an effective index of the light transmitted through said optical waveguide, and that an characteristic impedance of said traveling wave electrode approaches a characteristic impedance of an associated external circuit.

5. An electrically controlled optical device effective index according to claim 4, wherein said buffer layer is composed of a film of a polytetrafluoroethylene-type resin having a low dielectric constant.

6. An electrically controlled optical device effective index according to claim 4, wherein a slot is formed through at least one of said earth electrodes.

7. An electrically controlled optical device effective index according to claim 4, wherein a shield conductor is provided near to a region where said optical waveguide interacts with said traveling wave electrode, said shield conductor confronting said traveling wave electrode through an overlaid layer.

8. An electrically controlled optical device effective index according to claim 6, wherein a shield conductor is provided near to a region where said optical waveguide interacts with said traveling wave electrode, said shield conductor confronting said traveling wave electrode through an overlaid layer.

9. An electrically controlled optical device effective index according to claim 4, wherein said optical waveguide is disposed beneath said center electrode through said buffer layer, the width of said center electrode being at least generally equal to the width of a convex portion of said substrate including said optical waveguide therein, said convex portion being raised with respect to said recessed portions to said substrate.

10. An electrically controlled optical device ef-

fective index according to claim 9, wherein said width of said center electrode is slightly greater than said width of said convex portion of said substrate.

5 11. An electrically controlled optical device effective index according to claim 7, wherein said optical waveguide is disposed beneath said center electrode through said buffer layer, the width of said center electrode being at least generally equal to the width of a convex portion of said substrate including said optical waveguide therein, said convex portion being raised with respect to said recessed portions of said substrate.

10 12. An electrically controlled optical device effective index according to claim 11, wherein said width of said center electrode is slightly greater than said width of said convex portion of said substrate.

15 13. An electrically controlled optical device effective index according to claim 4, wherein said optical waveguide is disposed generally midway between said center electrode and one of said earth electrodes.

20 14. An electrically controlled optical device effective index according to claim 7, wherein said optical waveguide is disposed generally midway between said center electrode and one of said earth electrodes.

25 15. A method of producing an electrically controlled optical device effective index, comprising the steps of:

30 forming at least one optical waveguide, a buffer layer and electrodes on a surface of a substrate having electro-optic effects;  
35 subsequently fixing a conductor in the vicinity of said electrodes to cover the same.

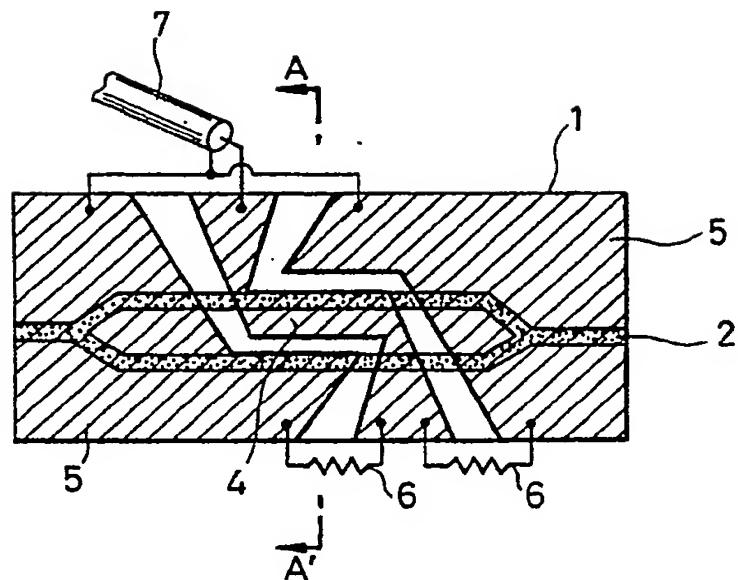
16. A method according to claim 15, wherein said conductor has a groove therein.

17. A method according to claim 15, wherein 40 an overlaid layer is provided between said electrodes and said conductor.

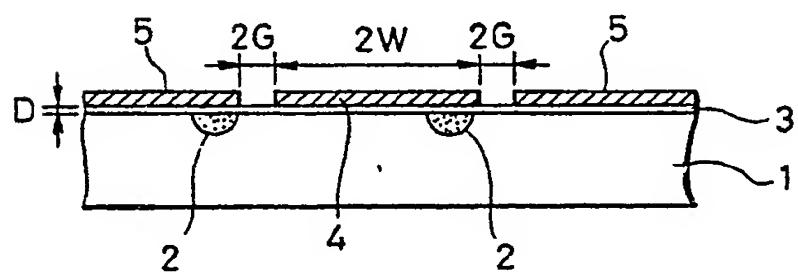
18. A method according to claim 15, wherein 45 said conductor is formed by metallizing a material which is used as a substrate in which an optical waveguide is to be formed.

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**FIG.1A** PRIOR ART



**FIG.1B** PRIOR ART

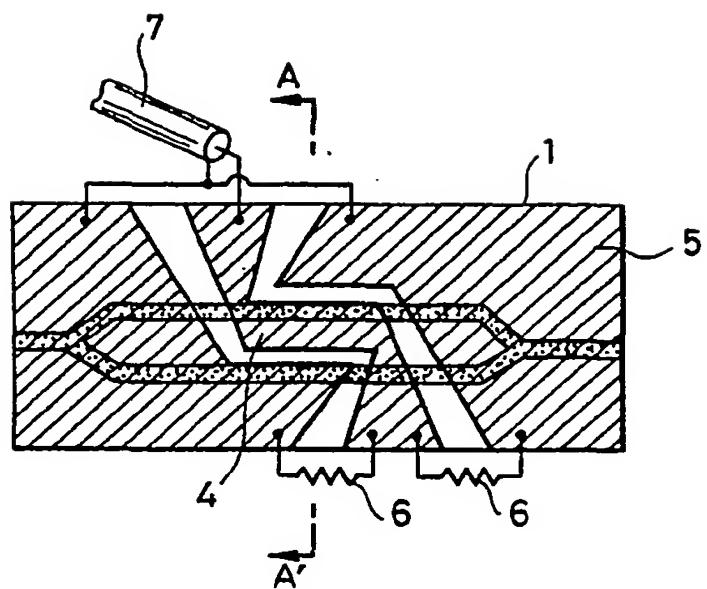


FIG. 2A PRIOR ART

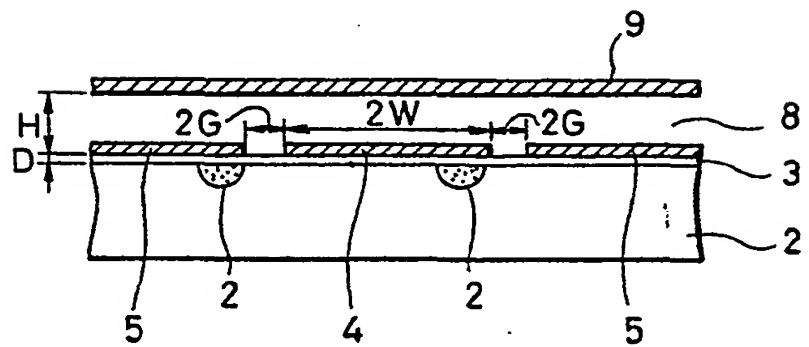
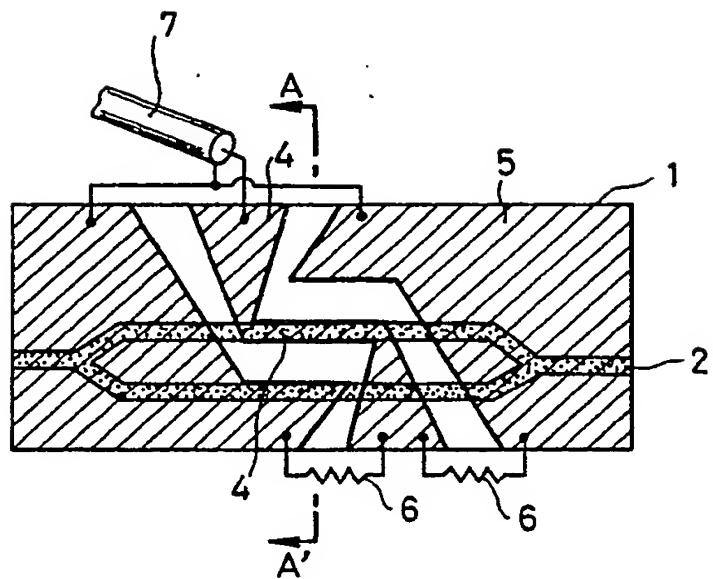
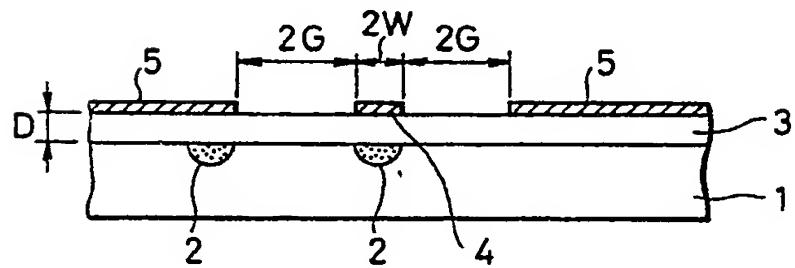


FIG. 2B PRIOR ART



**FIG. 3A** PRIOR ART



**FIG. 3B** PRIOR ART

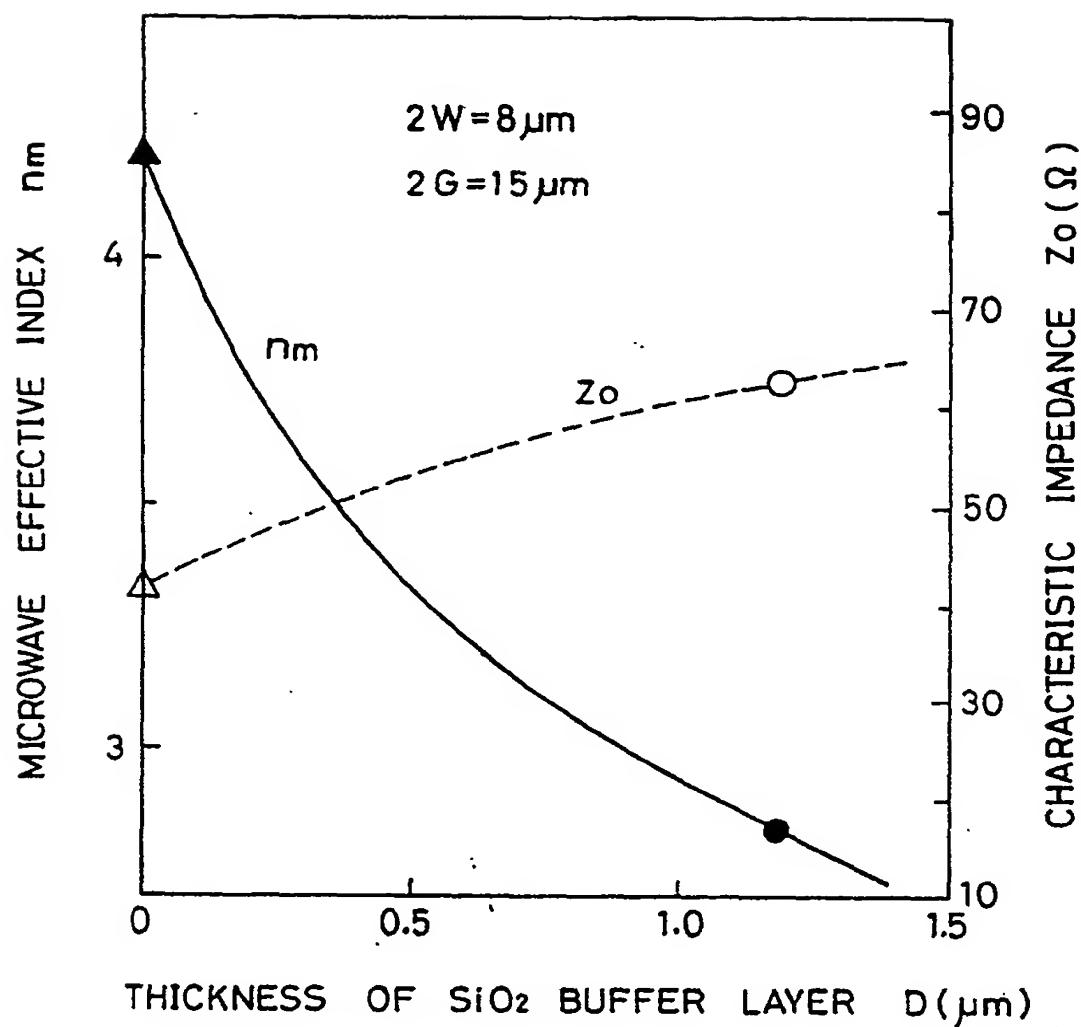


FIG. 4 PRIOR ART

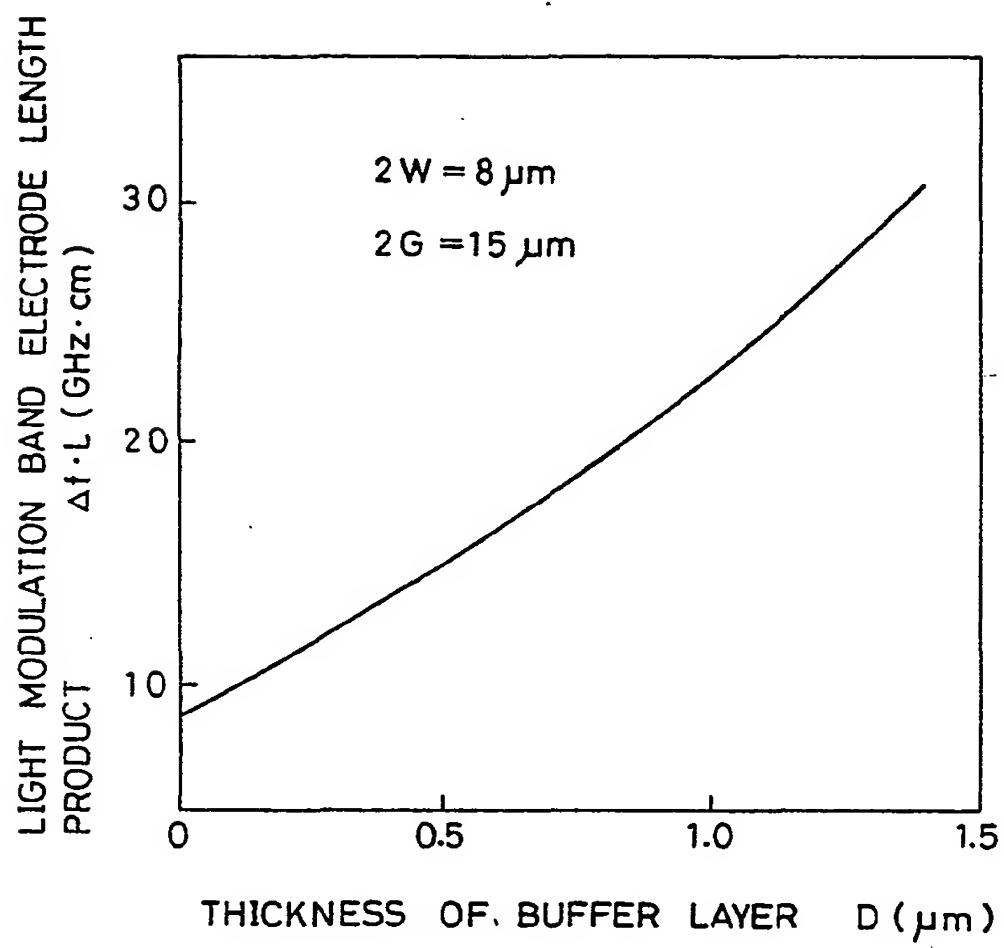


FIG. 5 PRIOR ART

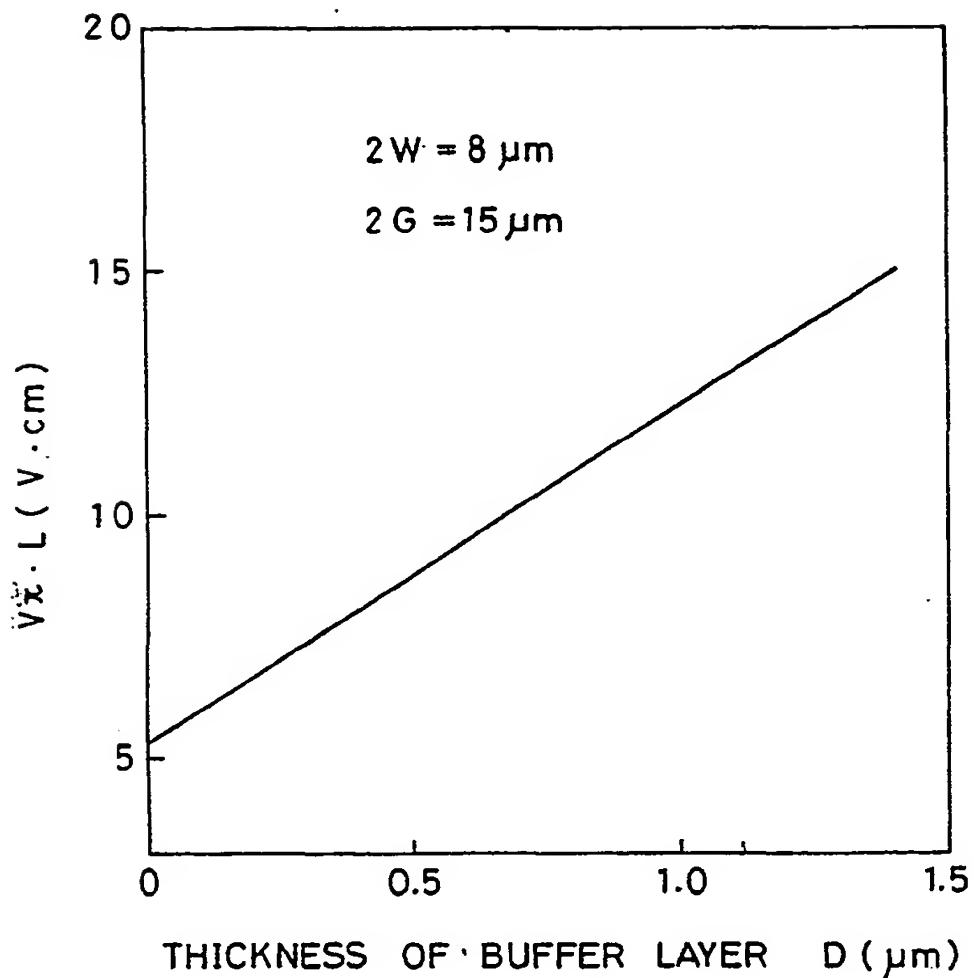


FIG. 6 PRIOR ART

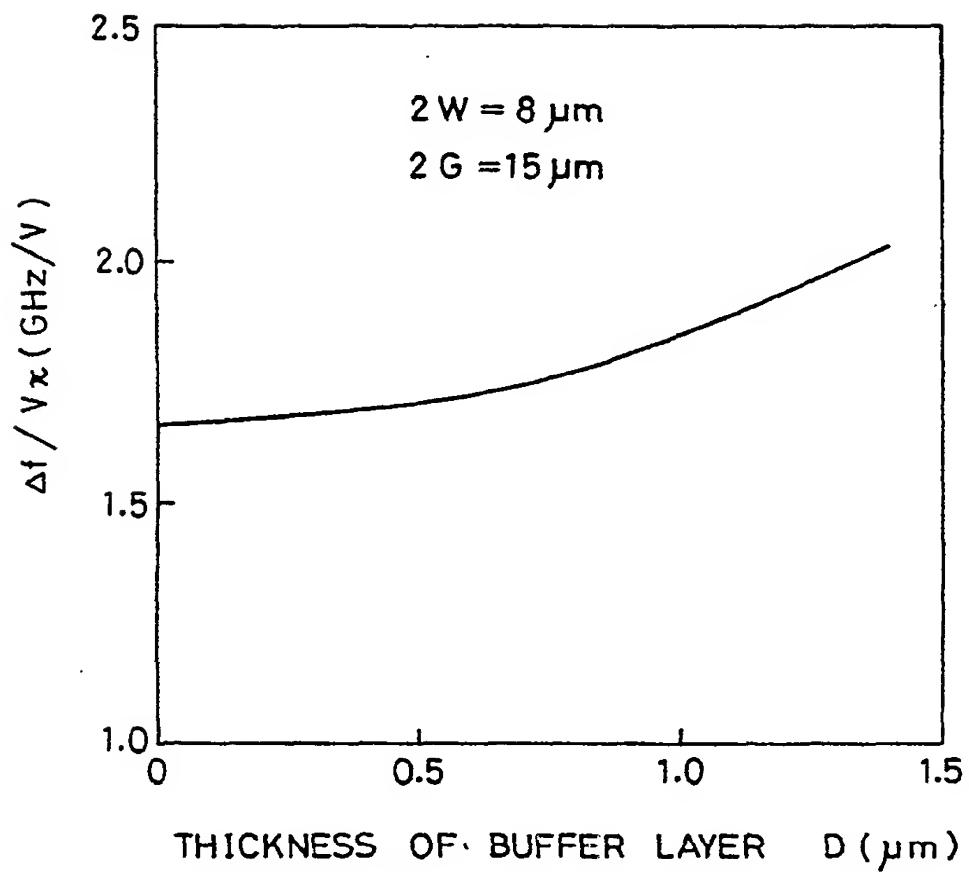
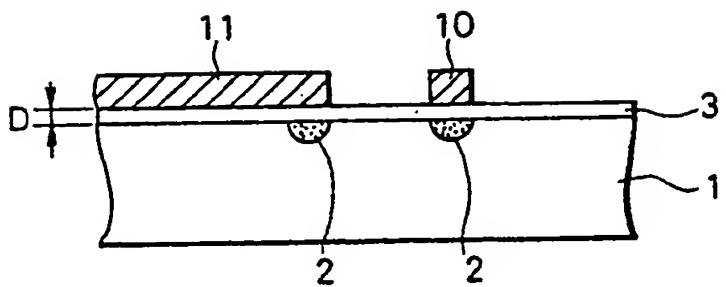
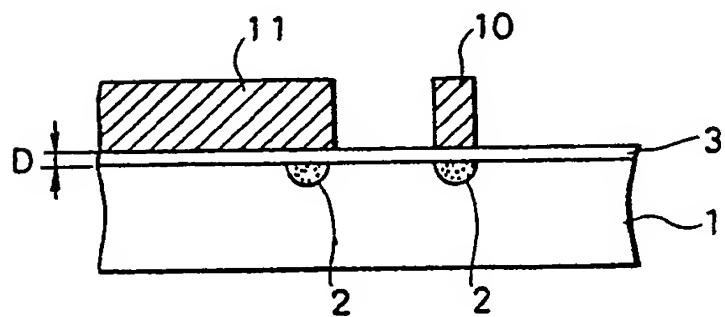


FIG. 7 PRIOR ART



**FIG. 8** PRIOR ART



**FIG. 9** PRIOR ART

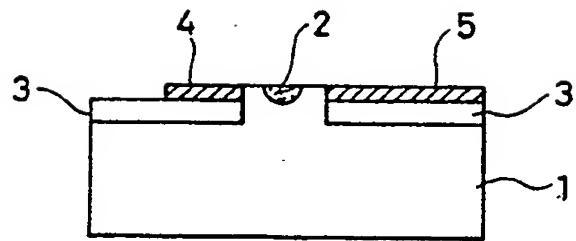


FIG.10 PRIOR ART

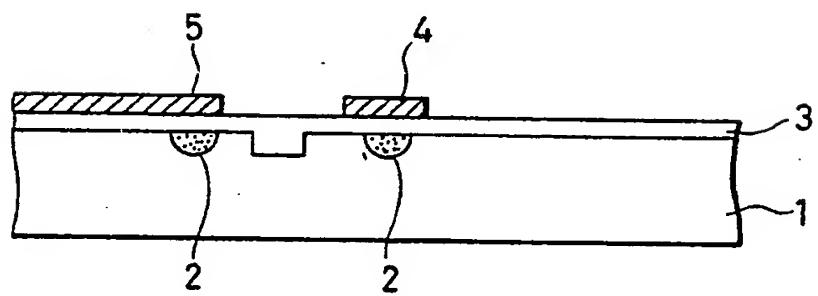


FIG.11 PRIOR ART

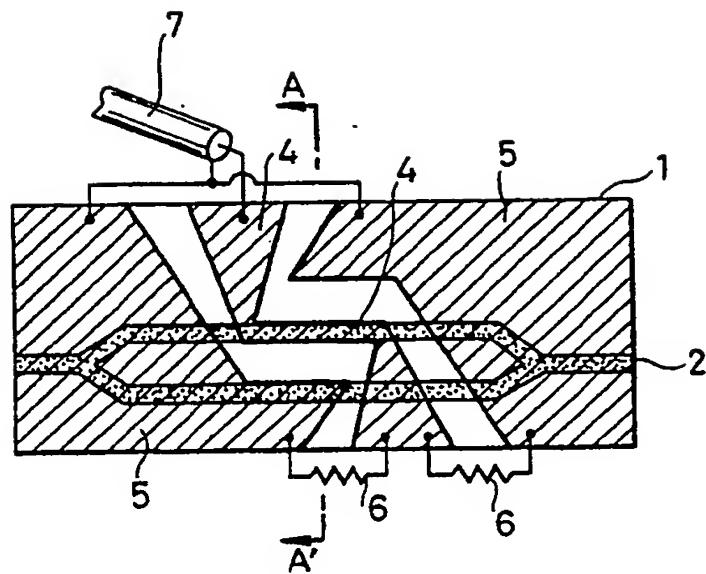


FIG. 12A

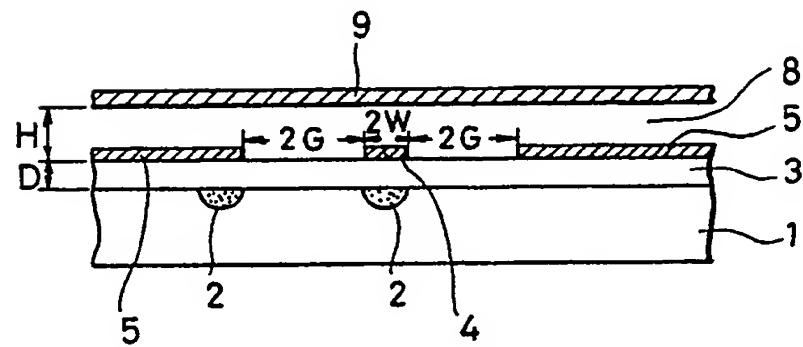


FIG. 12B

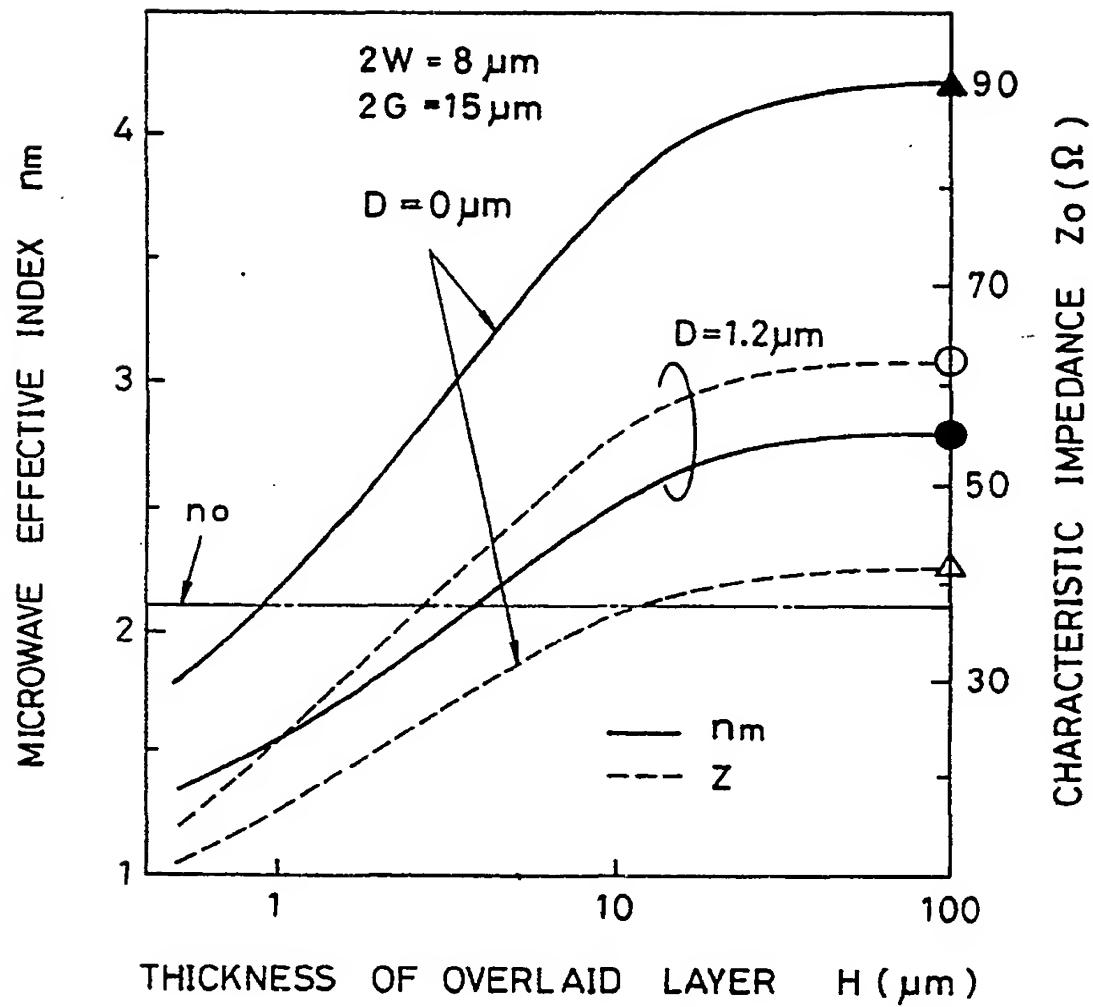


FIG. 13

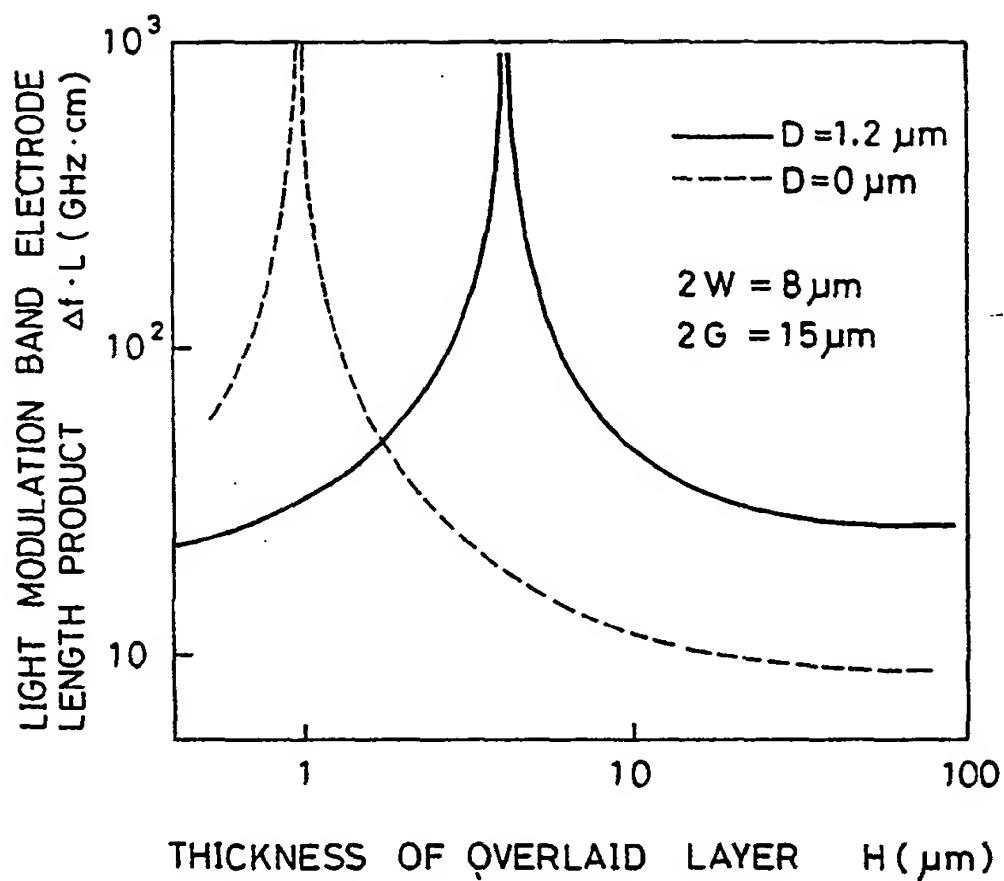


FIG.14

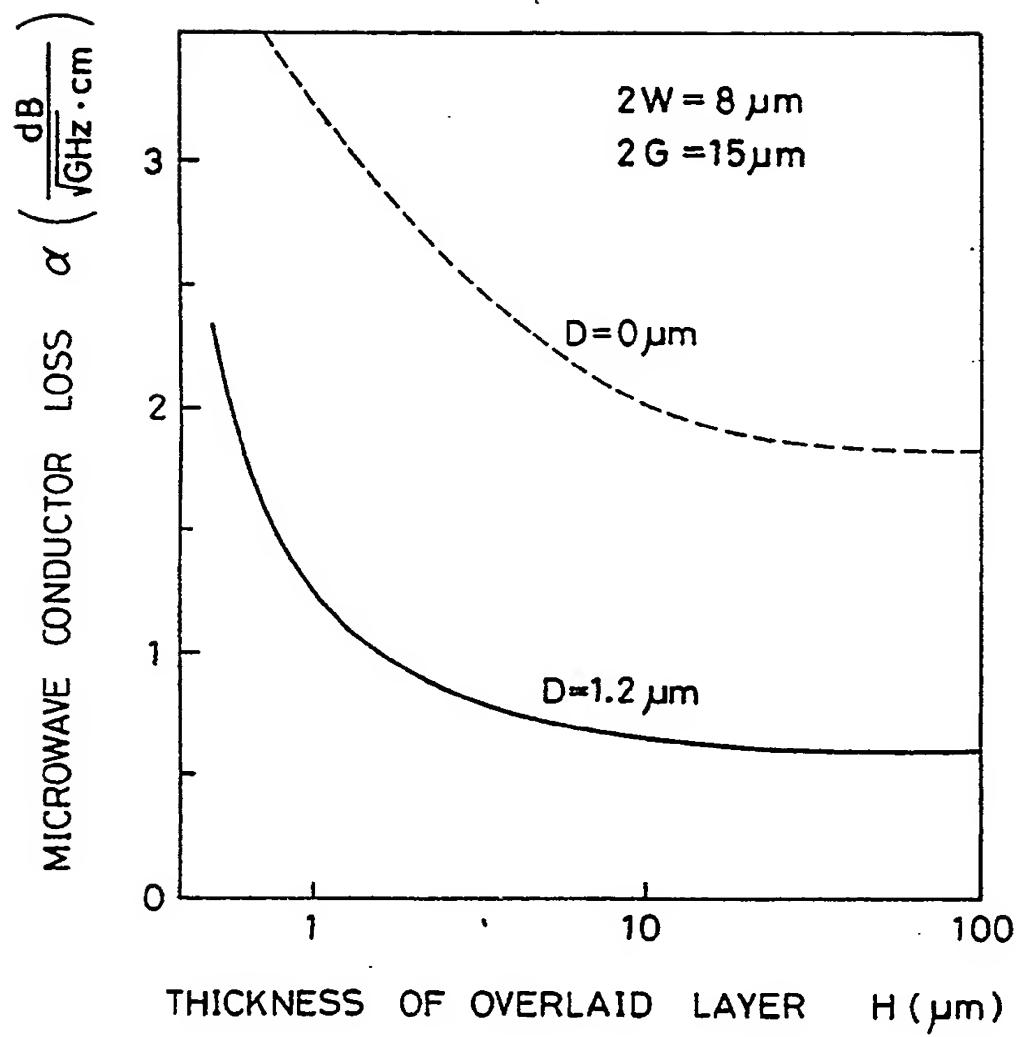


FIG. 15

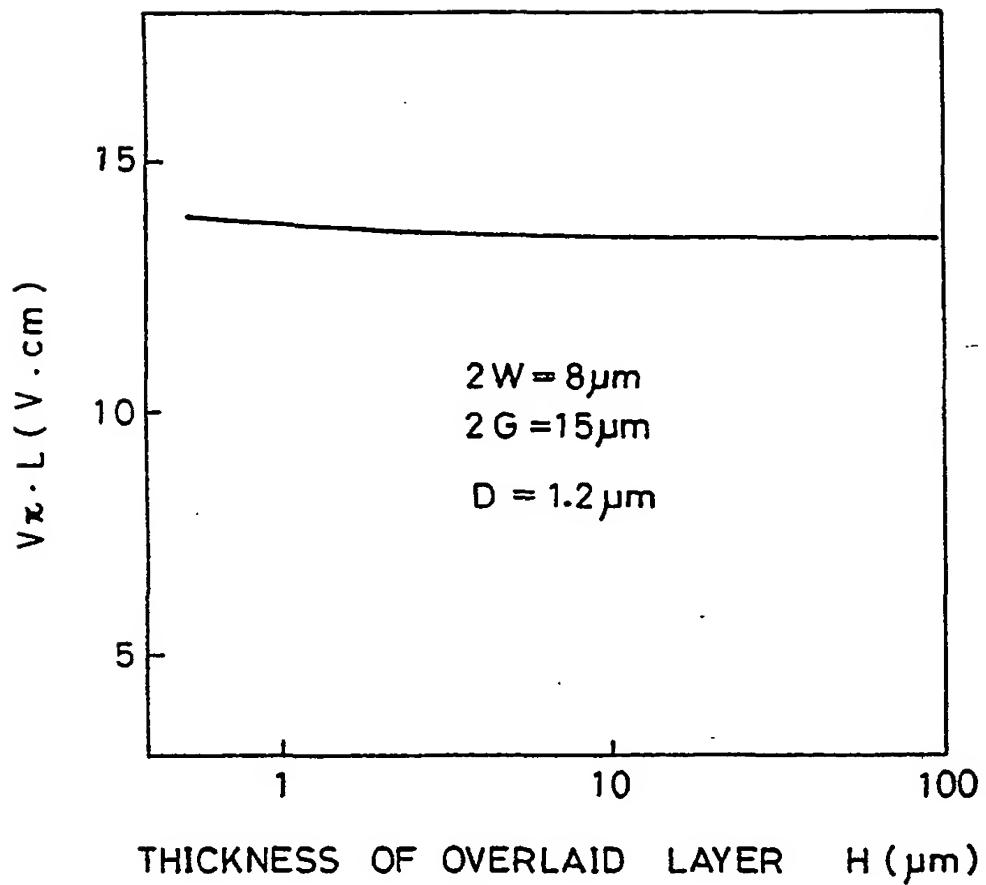


FIG.16

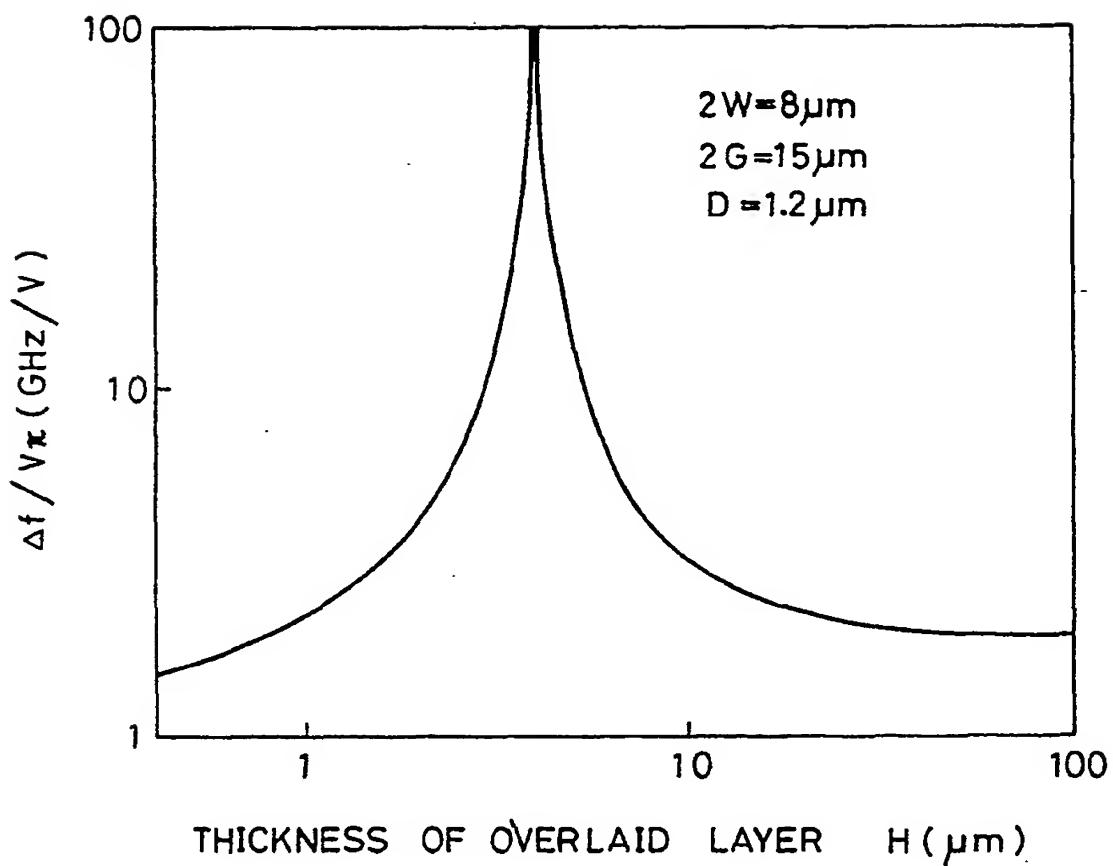


FIG.17

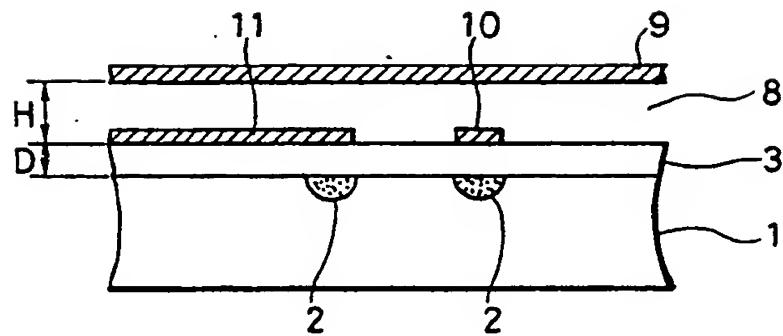


FIG.18A

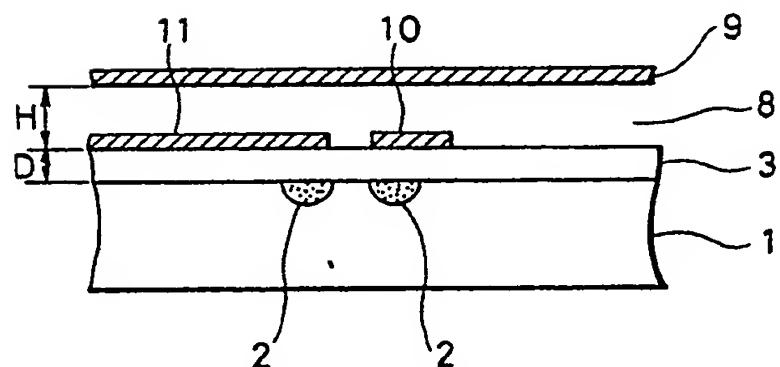


FIG.18B

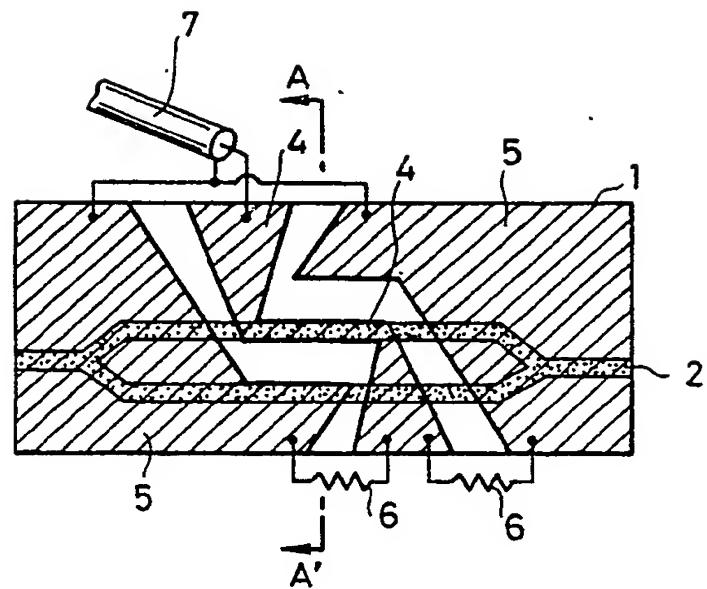


FIG.19A

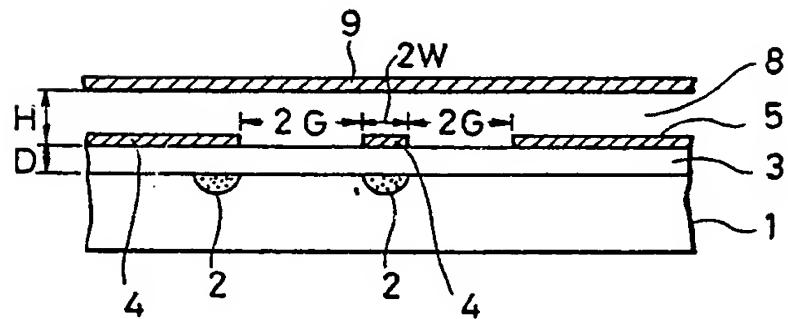


FIG.19B

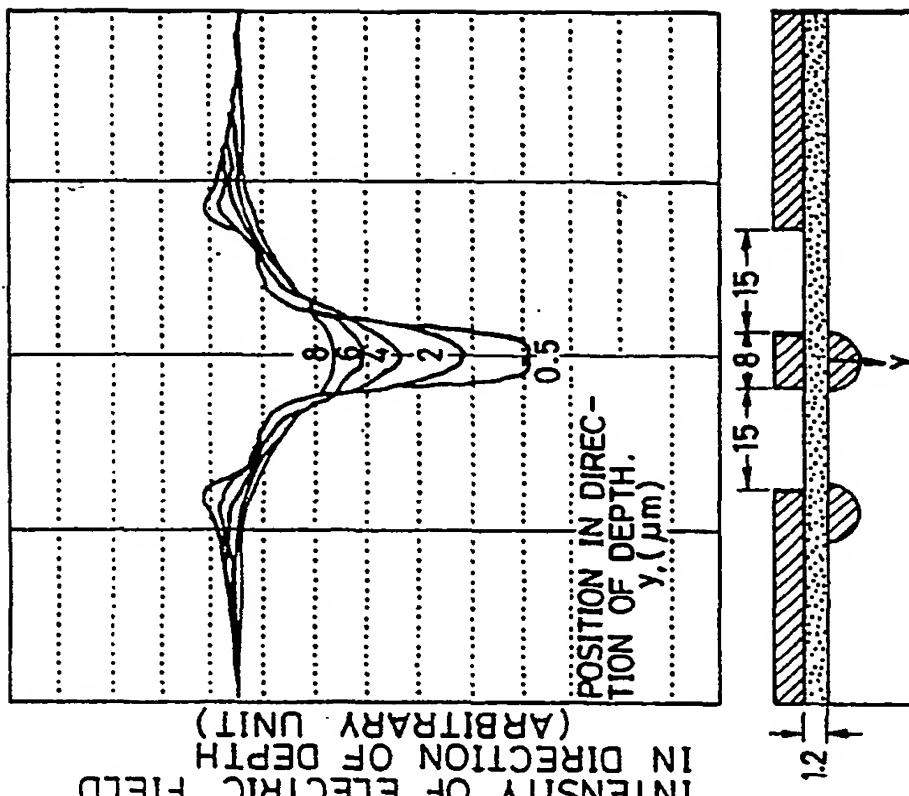


FIG. 20B

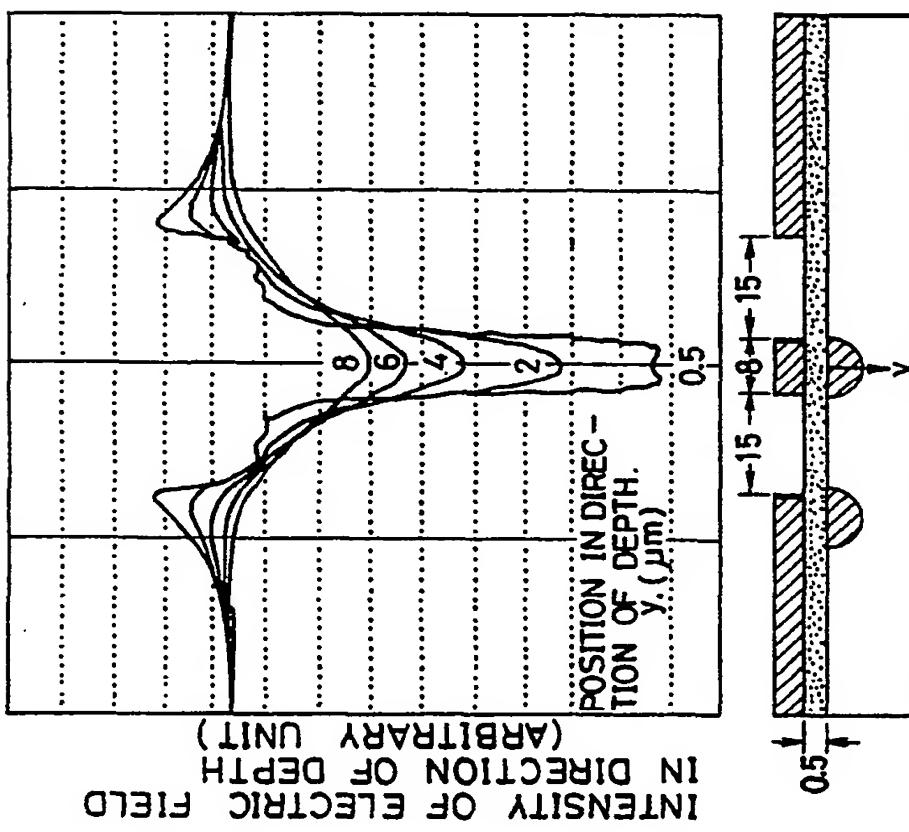


FIG. 20A

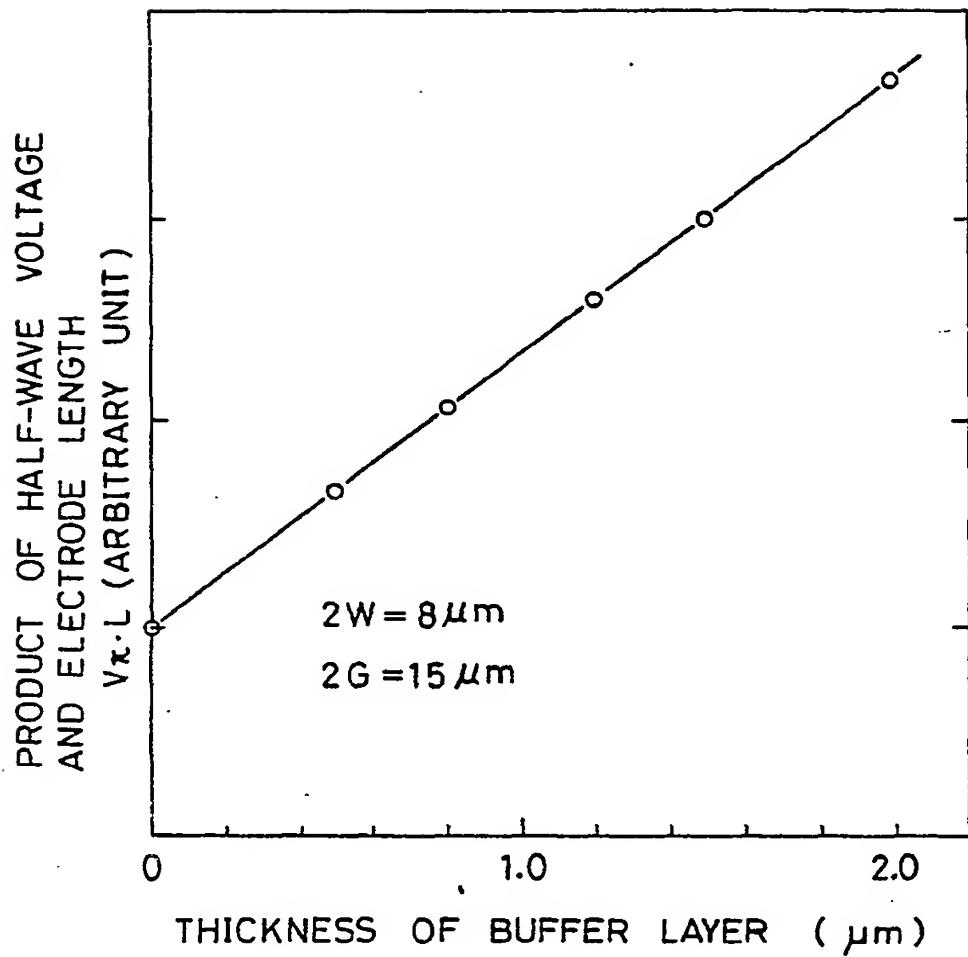


FIG. 21

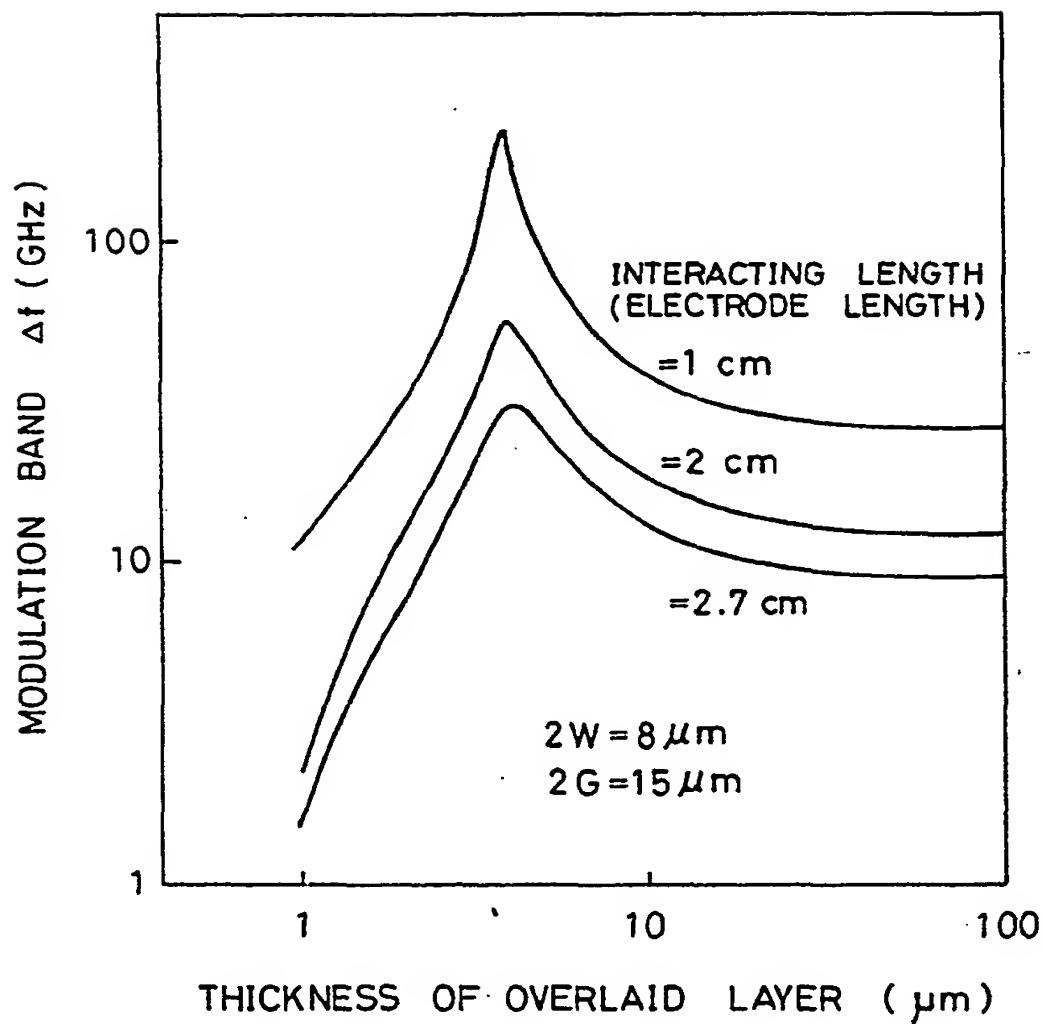


FIG. 22

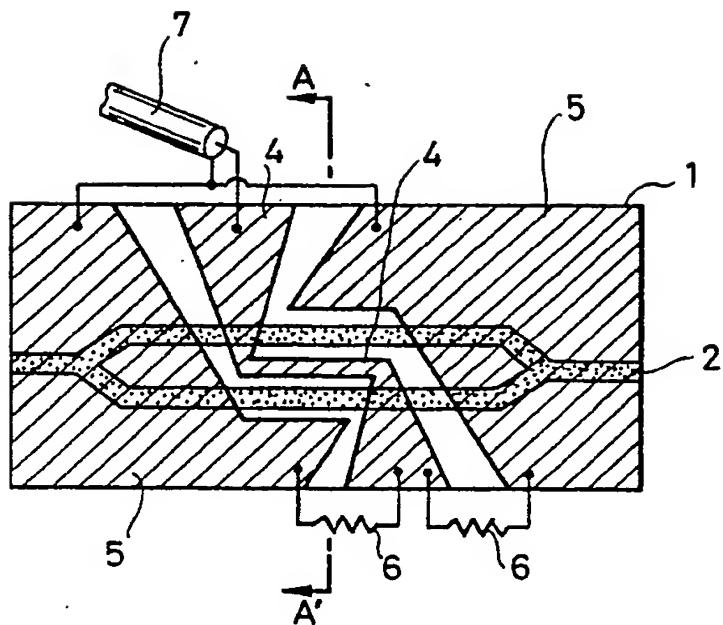


FIG. 23A

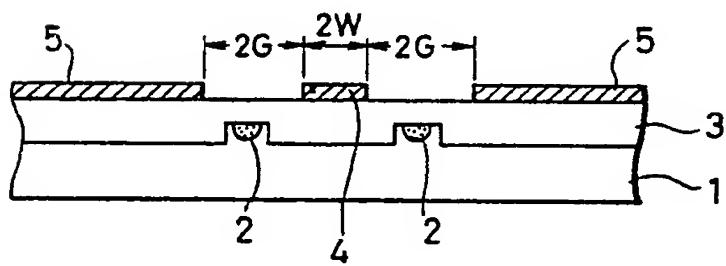


FIG. 23B

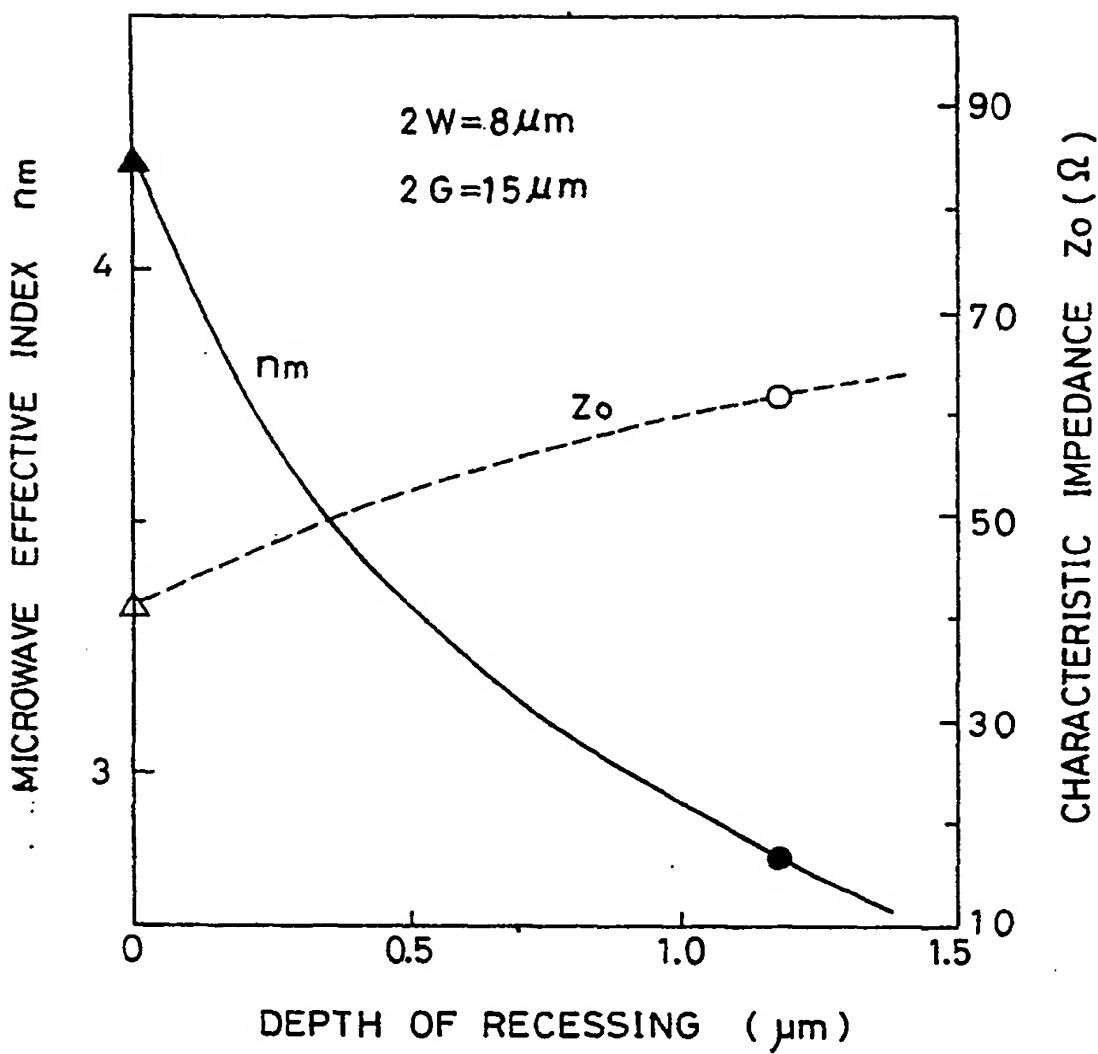


FIG.24

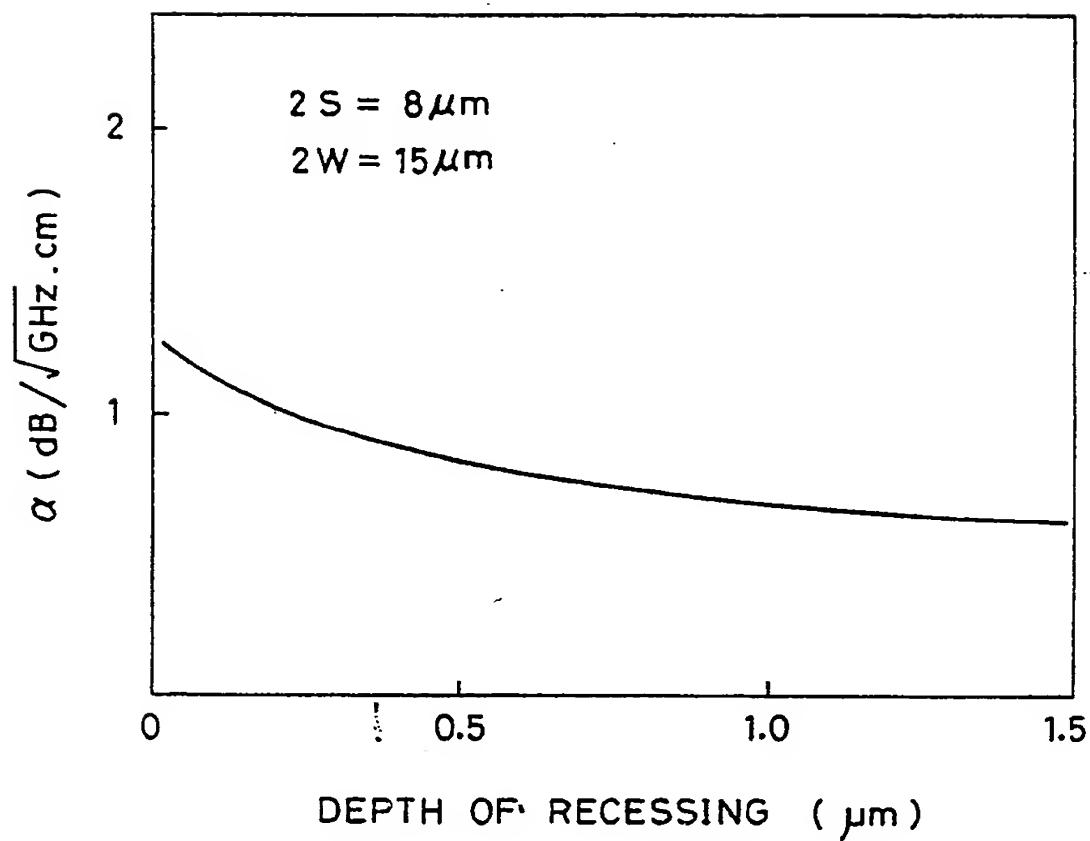
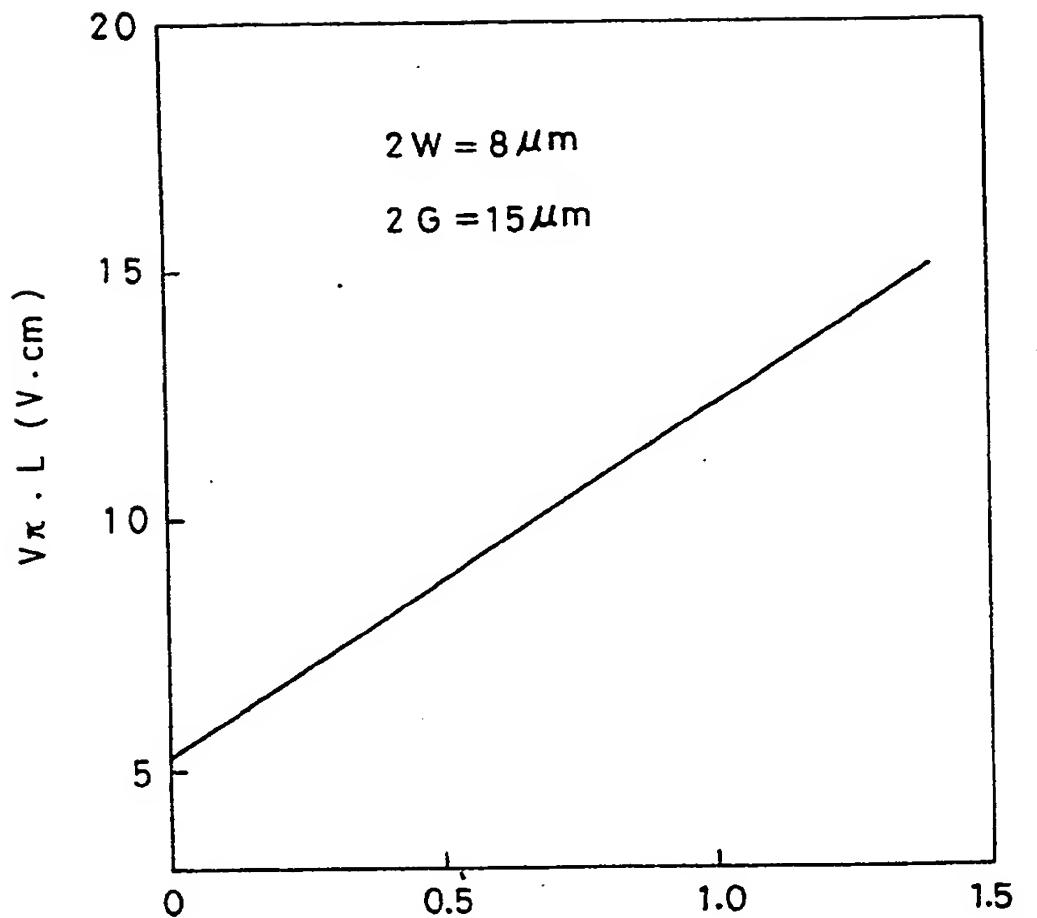


FIG.25



THICKNESS OF BUFFER LAYER JUST ABOVE  
OPTICAL WAVEGUIDE ( $\mu\text{m}$ )

FIG. 26

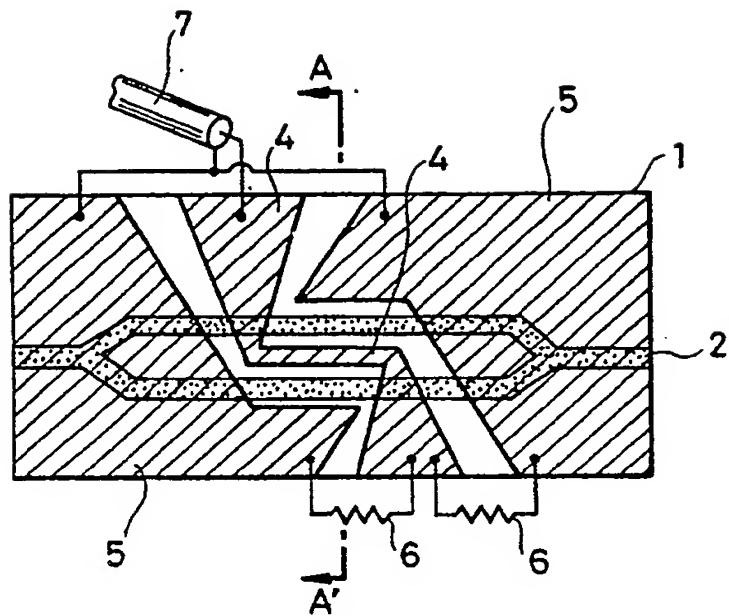


FIG. 27A

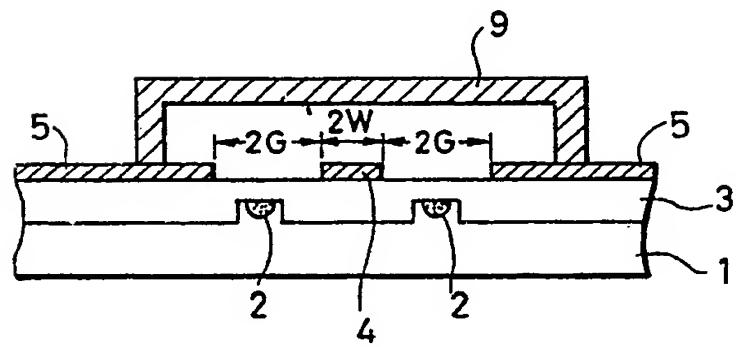


FIG. 27B

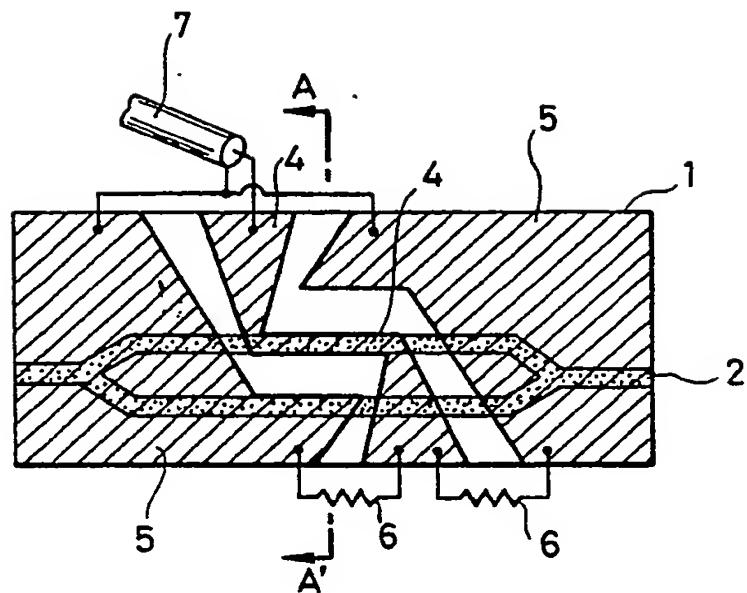


FIG. 28A

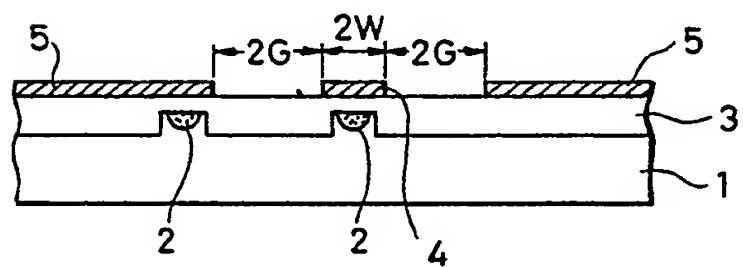


FIG. 28B

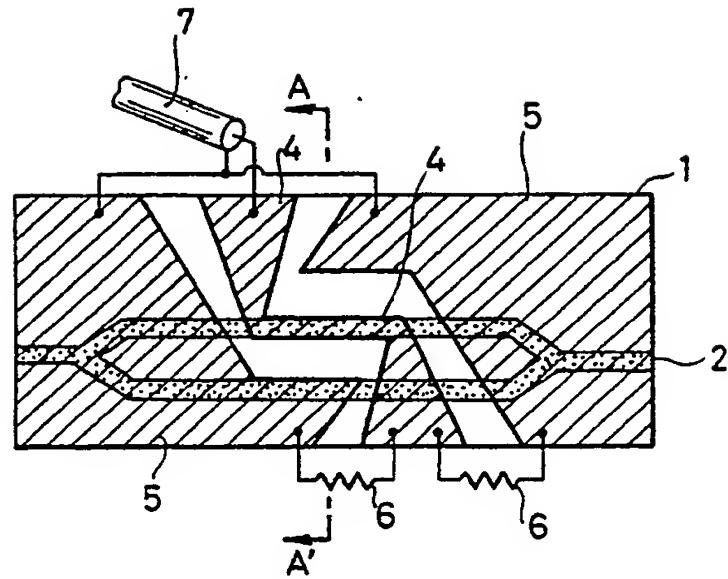


FIG. 29A

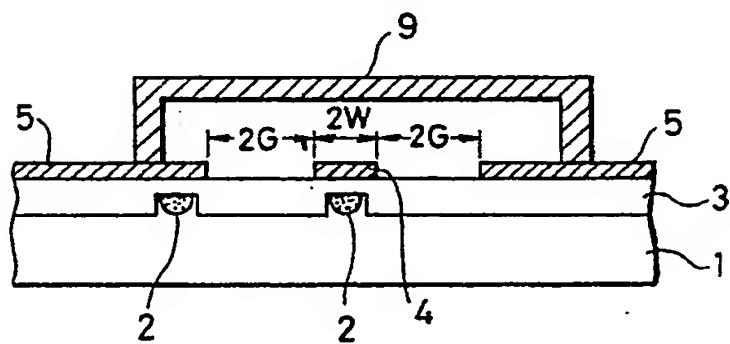


FIG. 29B

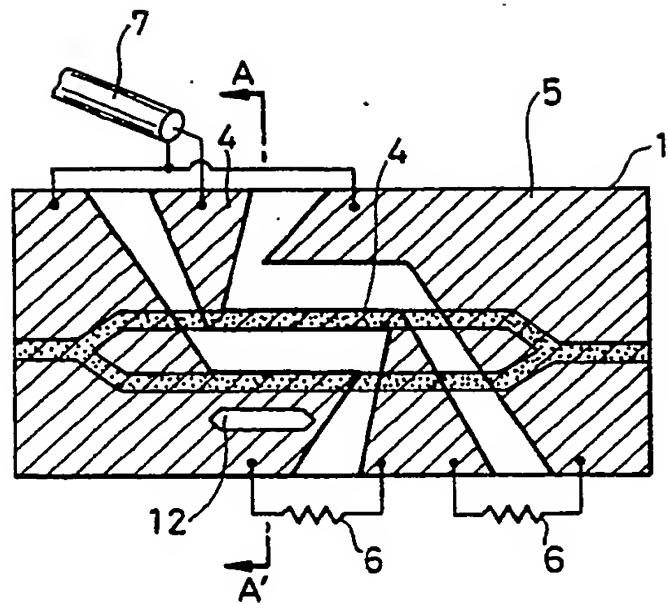


FIG. 30A

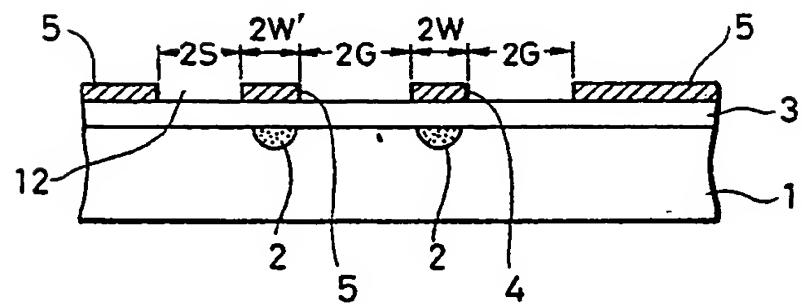


FIG. 30B

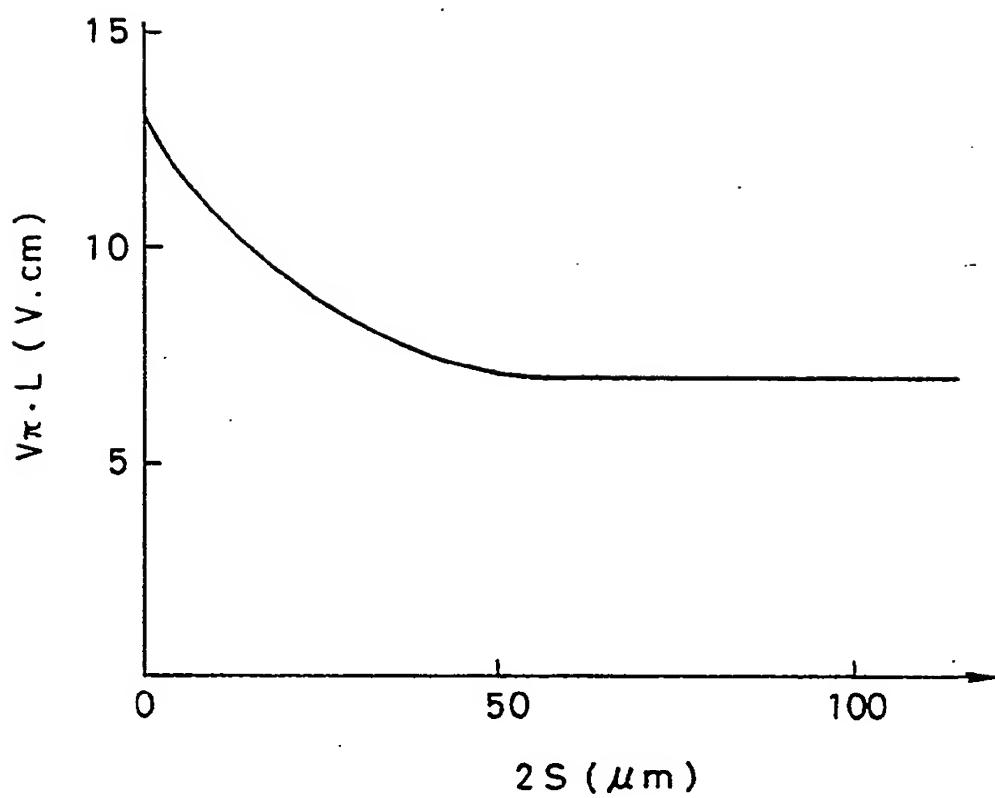


FIG.31

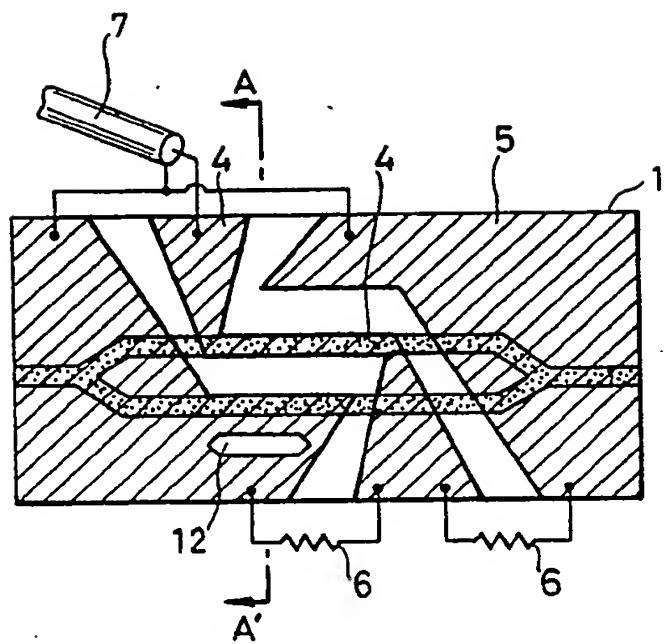


FIG. 32A

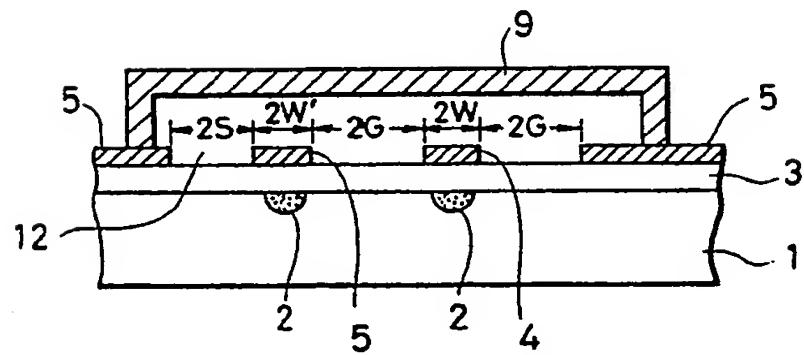


FIG. 32B

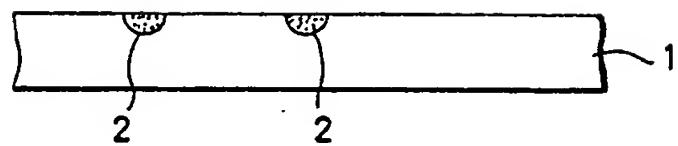


FIG. 33A

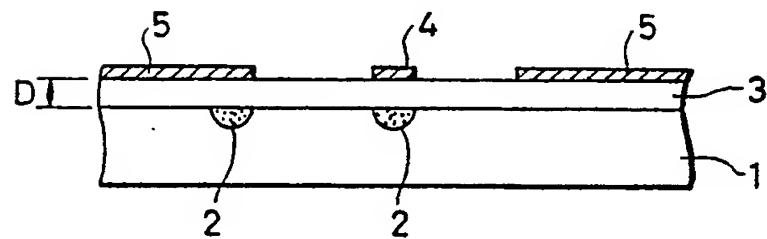


FIG. 33B

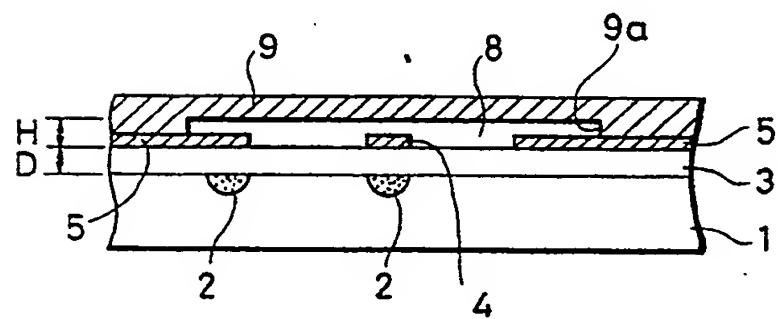


FIG. 33C



FIG. 34A

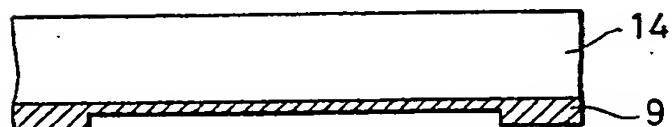


FIG. 34B

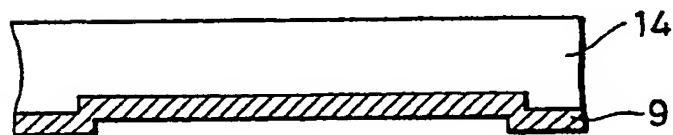


FIG. 34C

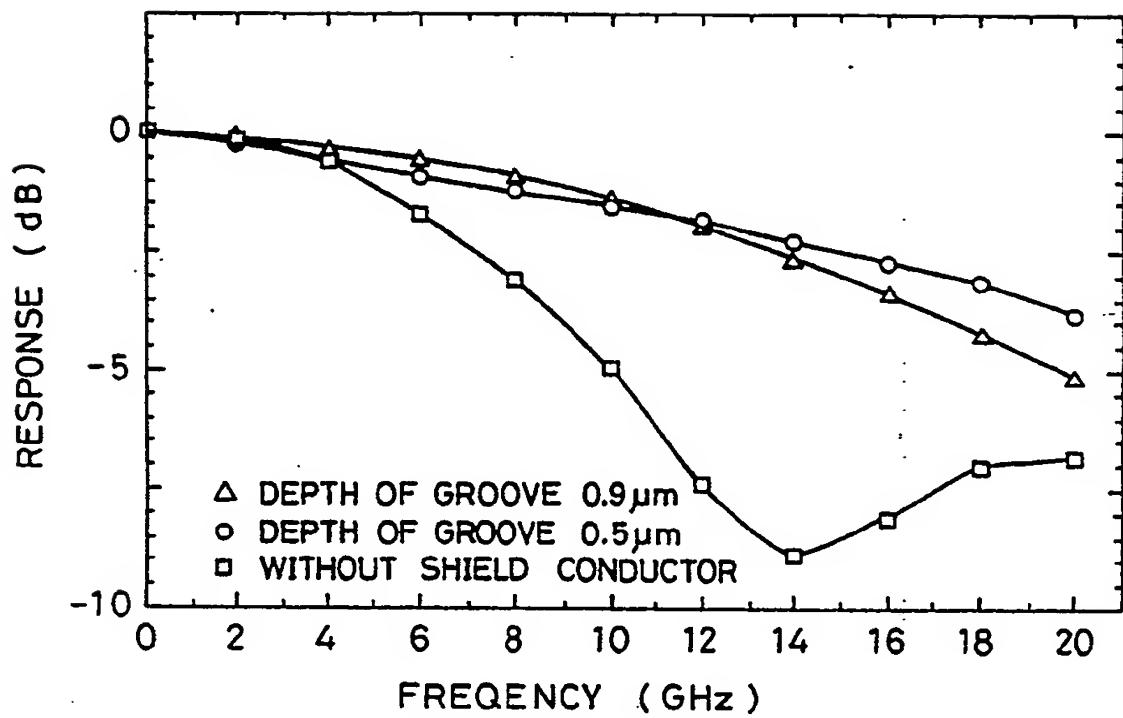
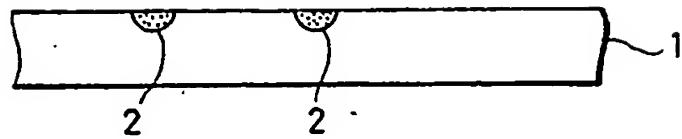
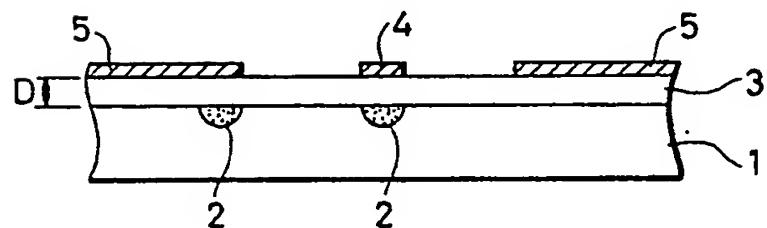


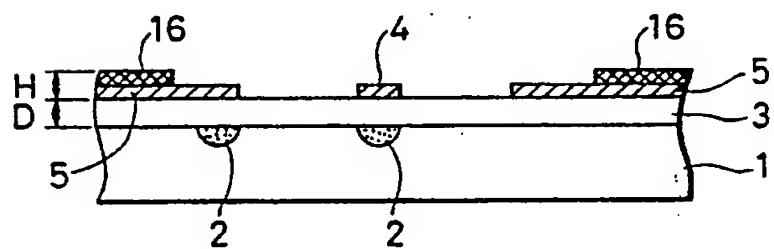
FIG.35



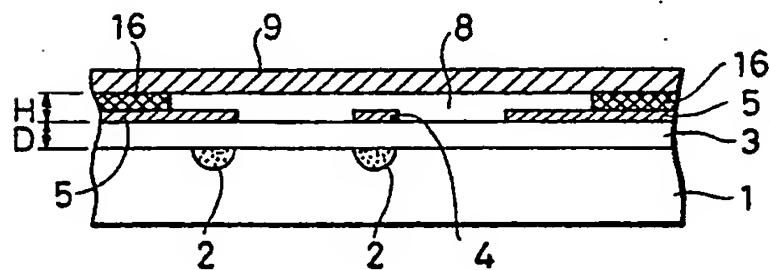
**FIG. 36A**



**FIG. 36B**



**FIG. 36C**



**FIG. 36D**



DOCUMENTS CONSIDERED TO BE RELEVANT			EP 90103043.7
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.)
A	APPLIED PHYSICS LETTERS, vol. 45, no. 11, December 1, 1984 R.A.BECKER "Traveling-wave electro-optic modulator with maximum bandwidth-length product" pages 1168-1170 * Totality; especially fig. 1 *	1, 4, 13, 15, 18	G 02 F 1/035 G 02 F 1/225
P, A	-- PATENT ABSTRACTS OF JAPAN, unexamined applications, P field, vol. 13, no. 245, June 8, 1989 THE PATENT OFFICE JAPANESE GOVERNMENT page 133 P 881 * Kokai-no. 1-48 021 (NIPPON) * & JP-A-1-48 021 (22.02.89) --	1, 4, 7	
D, P			TECHNICAL FIELDS SEARCHED (Int. Cl.)
A	EP - A1 - 0 233 797 (ETAT FRANCAIS) * Column 2, lines 43-54; column 3, line 10 - column 4, line 4 *	1, 4, 9	G 02 F
D, A	-- PICOSECOND ELECTRONICS AND OPTOELECTRONICS, Proceedings of the Topical Meeting Lake Tahoe, Nevada, March 13-15, 1985, Springer-Verlag, Berlin, Heidelberg, New York, Tokyo M.IZUTSU et al. "Ultrafast Traveling-Wave Light Modula- tors with Reduced Velocity Mismatch" pages 172-175	1, 4, 13	
The present search report has been drawn up for all claims			
Place of search	Date of completion of the search	Examiner	
VIENNA	21-05-1990	GRONAU	
CATEGORY OF CITED DOCUMENTS			
X : particularly relevant if taken alone	T : theory or principle underlying the invention		
Y : particularly relevant if combined with another	E : earlier patent document, but published on, or		
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EUROPEAN SEARCH REPORT

-2-

EP 90103043.7

DOCUMENTS CONSIDERED TO BE RELEVANT		
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim
	* Totality; especially fig. 3 *	
The present search report has been drawn up for all claims		
Place of search <b>VIENNA</b>	Date of completion of the search <b>21-05-1990</b>	Examiner <b>GRONAU</b>
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P : intermediate document	& : member of the same patent family, corresponding document	